Moving Away From the Traditional Desktop Computer Workstations: Identifying Opportunities to Improve Upper Extremity Biomechanics

Moving away from the traditional desktop computer workstations: Identifying opportunities to improve upper extremity biomechanics

Michael Yi Chao Lin

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Dissertation Advisor: Dr. Jack T. Dennerlein **Michael Yi Chao Lin**

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Abstract

Statement of Problem: Office computer workers have elevated risks of adverse health outcome such as musculoskeletal disorders (MSDs) associated with computer work. Although they now have many alternatives, these modern computer workstations and associated technologies require new guidelines and recommendations for proper practice. We see this as an opportunity to improve current and future computer workstation designs through an ergonomics approach by improving users' upper extremity biomechanics while interacting with these modern technologies.

Method: The dissertation first utilized a psychophysical protocol to compare users' self-selected set ups for sitting and standing computer workstations. Users' biomechanics and perceived comfort across different computer tasks for the two workstations are then compared. Subsequently, a hand mapping technique was developed to evaluate effects of computer pointing devices on users' hand posture and associated forearm muscle effort using 3-D motion analysis and surface electromyography. To improve mobile device ergonomics, we investigated tablet users' biomechanical load, comfort level and performance while performing swipe actions at different tablet locations.

Results: Different selected computer workstation set ups were found for sitting and standing. Compared to sitting, users while standing kept workstation components closer to their sternum and adopted a more neutral shoulder posture while working. However, users had greater wrist extension and started reporting more low back discomfort after 45 minutes. While investigating different computer pointing devices, we found device affordance associated with significantly different hand posture and forearm muscle load.

Devices that required less holding and were centrally placed associated with more neutral shoulder and hand postures, with significantly less forearm muscle load. For tablet interface, swipe locations closer to the palm had significantly smaller forearm muscle load and more neutral posture across wrist and thumb joints.

Conclusion: Through empirical results described in the dissertation, we demonstrated how users' upper extremity biomechanics can provide insights into the complex interactions between users and modern computer workstations, both as a whole and with specific components. For technology innovation, ergonomics concepts and methodologies can be used to design future generation technologies that fit users' physical capabilities to reduce MSDs risk while promoting performance.

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Thank you all for being a part of my life here at Harvard, I am forever grateful to you all.

Sincerely,
Michael Yi Chao Lin
Boston, Massachusetts
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Introduction

According to the U.S. Census Bureau (2005), a population survey revealed that more than half (56%) of employees over 18 years of age used computers at work, and the hours of computer usage per day is an average of 5.8 hours, which is 69% of the total working hours (Sommerich, 2002). With this trend of increased computer usage and long working hours with a computer, related work injuries have been documented, such as musculoskeletal disorders (MSDs); muscle, bone, and joint pain (Cherney, 2013) due to postural strain, repetitive movements, overuse, and prolonged immobilization ("Pain Management: Musculoskeletal Pain", 2015). One study by Gerr et al. found that 50% of computer users reported musculoskeletal symptoms after starting the first year of their new job, with 68% of the reported symptoms severe enough to be considered as a musculoskeletal disorder (Microsoft, 2013).

From a productivity perspective, working overtime and job demands that cause neck and back symptoms were risk factors of reduced productivity (Hagberg et al., 2007). More specifically, a significant number of men and women in a study group on self-reported productivity reported a reduced productivity due to musculoskeletal symptoms (Hagberg et al., 2002).

Additionally, sedentary behavior and inactivity have been reported as the leading causes of mortality, cardiovascular diseases, diabetes, obesity, colon cancer, high blood pressure, osteoporosis, lipid disorders, depression, and anxiety (World Health Organization, 2002). Since long working hours in front of the computer is a type of sedentary behavior, working environments and workstations should be a place for interventions in attempt to reduce these health risks, reduce related economic costs, and increase productivity.

Indeed, there has been focus on applying ergonomics in office settings. Studies have shown that successful office ergonomics programs can enhance worker health and well-being as well as increase organizational effectiveness (Robertson & O'Neill, 2003). Not only in North America, this is also evident in European countries, where a review showed that greater adherence to ergonomic design and assessment in work systems is likely the best strategy to reduce and prevent MSDs (Buckle, 2005). Moreover, Sauter et al (1991) have concluded that there is a relationship between workstations and musculoskeletal discomfort, and the participation of ergonomic design in the workplace increases employee comfort, and therefore productivity (Vink et al, 2006).

A traditional computer workstation often entails a seated desktop computer workstation which consists of a task chair, a desk that supports a monitor display, a full-size keyboard and a mouse. Recently, however, evidence has shown that we are moving away from these traditional seated desktop computer workstations. Laptop computers have for several years outsold desktop computers, and tablet computers are expected to out sell both desktops and laptop computers (Gartner Research, 2014). In fact, 31% of American adults now owns a tablet as of January 2013 and the number is still growing (Pew Research, 2013). Even for those that are still using desktop computers, standing computer workstations are now trending up to replace traditional sitting computer workstations.

Improving workstations with ergonomic research has continued throughout the decades, and guidelines have become available for setting up traditional computer workstations. Rempel stated that in the 1960s and 70s, the design of the split keyboard promoted neutral wrist posture, and became the number one selling keyboard in the U.S. in 2006 (Rempel, 2013). Also, the ISO 9241 and ANS/HFES 100 were standards developed that provided guidelines on adjusting the computer workstation chair and monitor height to decrease strain on the musculoskeletal system (Trudeau, 2013). However, my colleagues and I hypothesized that these guidelines for traditional workstations cannot be directly applied to modern workstations; as modern computer workstations do not always involve a seat, could involve a variation of pointing devices other than a mouse, and may be a mobile device instead of a desktop computer. We also believe that modern computer workstations interact with users differently than traditional ones. Since there is not yet a set of well-rounded guidelines to help computer users systematically choose and properly set up a modern computer workstation, new sets of usage guidelines and innovative methods for product design and evaluation are required.

Overall in addition, what we know is that variability in postures and working postures can improve health – sitting all the time is not good and standing all the time is not good. By mixing up activities, sedentary time is reduced and perhaps postural variability can be increased.

This dissertation will serve as a step to develop such guidelines. More specifically, ergonomic concept and research techniques are used to systematically analyze and evaluate modern computer workstations: from general workspace setup, specific device selection, to interface usability comparison. As illustrated in Figure 1, our MSD risk model is based on the fact that workstation design, interventions, and computer work tasks require different motor controls from users. These motor controls, which essentially reflect how users interact with the workstation, induce different levels of biomechanical load from the users. Excessive biomechanical loads, including awkward postures and extended muscle activation, are known to be major risk factors of musculoskeletal disorders. Through this risk model, this dissertation will serve as recommendations to help understand how workstation and specific component design affects users' work performance, posture, muscle activation and perceived comfort, in order to make recommendations for device design and workstation set up guideline development. The dissertation objective was to help manufacturers and users on improving proper usage of modern computer devices and workstations, which is believed to improve work productivity, and decrease computer-work related injuries and health risks.

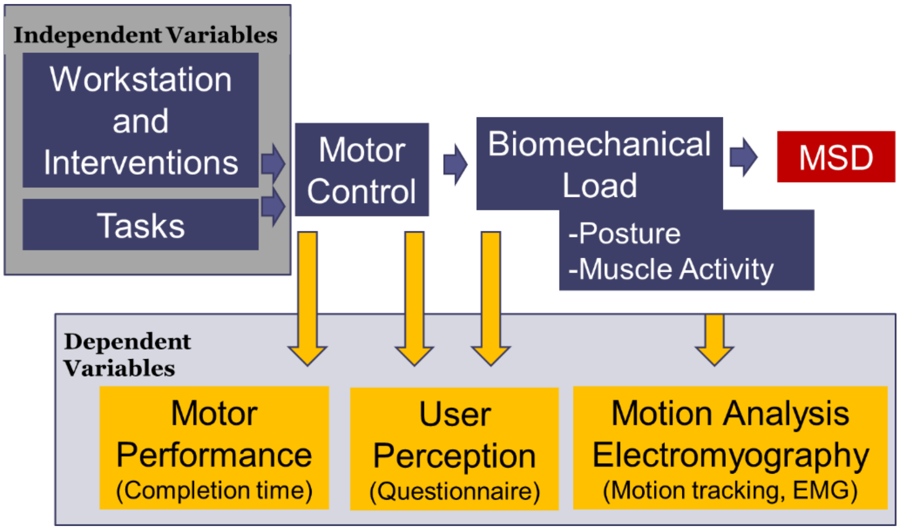

Figure 0.1: Musculoskeletal Disorders Risk Model

This objective has been carried out with 3 main focuses, corresponding to the chapters in this dissertation. Chapter 1 and 2 focus on utilizing a psychophysical protocol to compare users' experience with sitting and standing computer workstations. It is done by evaluating users' self-selected workstation configurations, biomechanics and perceived comfort across different computer tasks. This will mark the first psychophysical protocol used to link computer users' self-selected workstation setup with their biomechanical load and comfort level, specifically for standing workstations. These two chapters can aid in developing guidelines to set up a standing computer workstation, and in the meantime providing evidence that guidelines for a standing computer workstation cannot simply be adopted from a sitting computer workstation.

Upon completion of workspace setup, chapter 3 shifts focus on providing insights on choosing and evaluating appropriate pointing devices. Using 3D motion analysis, a hand mapping technique to measure hand posture was developed to provide better understanding of the relationship between computer pointing device affordance and users' hand-finger postures. Such findings will help explain differences in forearm muscle activity levels across devices and complement previous research that focused on shoulders and wrists.

Finally, chapter 4 focuses on tablets. As there are now increasing office workers who use mobile devices rather than desktops for work, this chapter provides innovative findings that will connect tablet input interfaces with users' biomechanical load, comfort level, and motor performance. Such information will help users work more efficiently and comfortably with their current interface. It will also help software developers design future interfaces that minimize users' discomfort without sacrificing work efficiency.

Chapter 1

A Psychophysical Protocol to Develop Ergonomic Recommendations for Sitting and Standing Workstations

Abstract

This study applied a psychophysical protocol to determine user self-selected setup for both sitting and standing computer workstations. Twenty adult (10 female, 10 male) participants completed four 45-minute sessions of simulated office computer work with an adjustable sit-stand computer workstation. Placement and relative position of all workstation components, including a cordless mouse, a cordless keyboard (without a number pad), a height-adjustable desk, and a 22" monitor mounted on a mechanical-assisted arm were recorded during the 4 sessions that alternated between sitting and standing for each session. Four times during each 45-minute session, the placement of these components were placed at extreme locations and participants were instructed to adjust the location (height, distance, and angle) to achieve the most comfortable arrangement and to make as many adjustments during the session to achieve this goal. Overall, users placed the keyboard closer to their body (sternum), set desk (keyboard and mouse) height lower than their elbow and set the monitor lower relative to their eyes with a greater upward tilt while standing compared to sitting. During the 45 minute sessions, the amount of adjustments participants made became smaller and over the 4 sessions were consistent suggesting the psychophysical protocol was effective and consistent. These results can serve as the first step towards making recommendations to establish ergonomic guidelines for standing computer workstation arrangement that may call for a different setup principle compared to sitting.

Introduction

In most developed countries, office workers typically sit close to 6 hours a day just for work alone (Brown et al., 2003). One popular approach to reduce prolonged sitting and increase physical activity is through the use of standing workstations. However, this rapid shift to standing workstations often takes little consideration to the ergonomic or biomechanical factors guiding how the workers should set up their standing workstations. The removal of the task chair may increase musculoskeletal disorders (MSDs) risk for workers due to physiological factors associated with the removal the torso and arm support that the chair typically provides (Taillefer et al., 2011, Marshall et al., 2011; NelsonWong et al., 2010). However, the effects of computer workstation set up for standing conditions has not been explored, especially compared to the numerous studies exploring the configuration of sitting computer workstations. Yet, when searching for specific guidelines for workstation set up for standing we found no specific recommendations on how to set up a standing workstation.

Currently, there are existing guidelines such as the ones by Occupational Safety and Health Administration (OSHA) for sitting computer workstations which state that the desk should be set at resting elbow height and the top of the monitor should be set slightly below eye-level to reduce risk of MSDs and symptoms (OSHA, n.d.). Though OSHA guidelines do exist for general standing work, they are not specifically oriented towards office computer work and do not incorporate the multiple components of a computer workstation that may include a keyboard, a mouse and a monitor. It is our impression that the current approach for a standing workstation setup is merely adapted from the sitting workstation guidelines; however, with the chair and its associated support of the user's body no longer present, we do not believe that the same guidelines for sitting workstations can be simply translated to standing workstations.

One approach to developing recommendations can be through the use of psychophysical protocols where a user searches various configurations to determine the configuration that provides the best comfort. Psychophysical methods are widely used throughout the ergonomics and human factors community. A classic example is the Snook & Ciriello Tables for lifting, which cover many different types of lifting scenarios and have been incorporated into the development of the National Institute of Occupational Safety and Health (NIOSH)-sponsored lifting equation that provides recommendations for limits in weights for lifting. Overall, psychophysical methods rely on a user's perception of what is acceptable by aiming to minimize the user's overall discomfort (Snook, 1995). For computer workstation configurations, previous studies have investigated user's preferences towards how a monitor display is set up, in terms of display distance and angle, and its effect on user's neck posture (Shin and Hegde, 2010; Young et al, 2012; Camilleri, 2011).

The primary objective of this laboratory study was to document users' preferred sitting and standing computer workstation setup that include desk height, keyboard, mouse, and monitor positions using a psychophysical protocol. We propose this approach as a step to developing guidelines for standing computer workstations. For secondary objective, we intend to analyze the user variability and consistency of measurement, and convergence of work station measures over time to evaluate the effectiveness of the psychophysical protocol as a method to determine user's preferred workstation setup. We hypothesize that the selected workstation set up for standing in terms of desk height, keyboard/mouse position, and monitor position relative to the user will be different than that for the sitting set up. We also hypothesize that user's selected set up for the two sessions they complete with the same sitting/standing workstation will be similar.

Methods

Twenty right-handed adult participants (10 females, 10 males) with no history of neck or upper extremity musculoskeletal injuries volunteered. Although no inclusion/exclusion criteria were set for workstation experience, all participants had experience working with a sitting computer workstation but none had experience working with a standing workstation. The mean anthropometric measures for the participants were typical of the average United States population (Table 1.1). Northeastern University office and committee on Human Subject Research Protection approved all protocols and informed written consent forms.

	Males (N=10)	Females (N=10)	All
Age (yrs)	29 (5)	26(5)	27.4 (5)
Height (cm)	179 (6)	164 (5)	171 (9)
Weight (kg)	81 (18)	61 (11)	71 (18)
Hand Length (cm)	19 (0.9)	18 (0.6)	18 (1.1)
Hand breadth (cm)	9.6 (0.6)	8.3 (0.4)	9 (1)
Shoulder width (cm)	44 (3)	40 (2)	42 (3)
Forearm length (cm)	46 (2)	41 (2)	44 (3)
Chair height (cm)	49 (2)	47 (1)	48 (2)

Table 1.1: Anthropometric measures of means (standard deviations) across all participants

After initial instrumentation setup, all participants completed the full 3-hour psychophysical study protocol (Figure 1.1) using the same sit-stand workstation consists of a height-adjustable desk (Airtouch®, Steelcase), a wireless mouse (M325®, Logitech), a wireless keyboard (Slim Bluetooth keyboard, Hewlett-Packard), and a 19-inch LCD monitor (DELL) supported with an easy-to-adjust mechanical arm (LX Desk Mount LCD Arm ®, Ergotron). For the seated conditions, the participants used a task chair (Ergonomic Task Chair, casted by Superior Furniture, TX) without arm rests. The chair height adjusted by the experimenter such that the participant's feet could remain on the floor and the thighs would be parallel with the floor throughout the experiment.

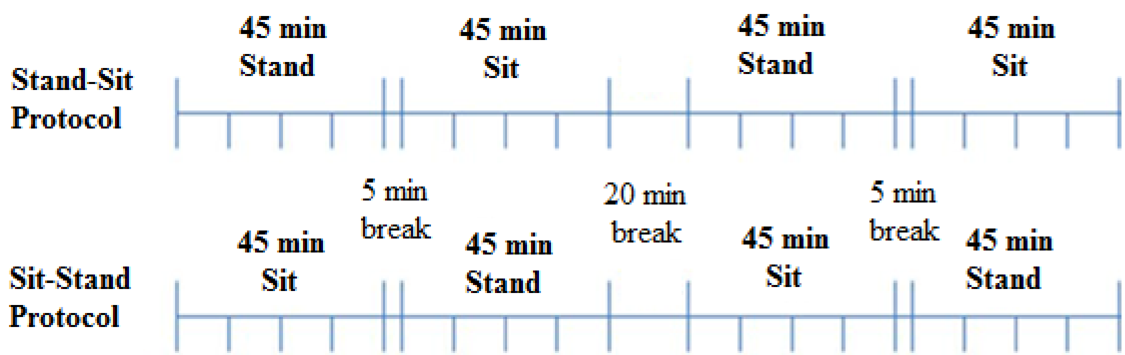

Figure 1.1: Psychophysical protocol that includes four 45-minute sessions, each session had four 11 ¼ minute segments. Each tick represents the end of the segment, when the workstation was set to extreme position and the user had to readjust the workstation. The order for which participant begins with sitting or standing was counterbalanced. Participants were offered a 5-minute break between the first and the third session, and a 20-minute break after they have finished the first two sessions.

Psychophysical protocol

The psychophysical protocol consisted of four 45-minute sessions, each alternating between sitting and standing (Figure 1.1). The 45-minute duration was chosen so that each session would be long enough for users to potentially develop early sign of fatigue or pain, if any, under each workstation setting (Gallagher, 2014). Every 11.25 minutes the experimenter interrupted the user and set the workstation to one of several extreme positions, requiring the participant to readjust the height of the desk, the position of the keyboard and mouse, and the 3-D position and angle of the monitor to her/his preferred working locations. The participants faced the opposite direction to avoid viewing the resetting of the workstation. The instructions for the participant were, "Adjust the height of the desk, the position of the keyboard and mouse, and the position and angle of the monitor to minimize discomfort as if you were to work in this posture for a whole 8 hour day. You may continue to make as many adjustments as you like, even in the middle of your task whenever you feel like to, and even if you have not make any adjustments for some *time."* These instructions were derived from those associated with the psychophysical methods of Snook and Ciriello (Snook, 1995). The printed instructions were provided and read to all participants at the beginning of the protocol. Short sentences of reminders were posted by the monitor and the keyboard to encourage the participants to continue making adjustments to find their most comfortable set up.

During the protocol, the customized office tasks included answering emails, constructing Microsoft Excel ® spreadsheets, editing essays and playing simple pattern-matching games. All tasks were designed to simulate daily office work activities that may involve transcribing texts, completing Internet research, data entry, writing small correspondences, and gaming. These tasks involved different levels of both cursor operations (cursor movement, point-and click and click-and-drag) along with intermittent keyboard operations (typing) to simulate office work that often requires interactions with both the keyboard and the designated pointing device. The overall task completion required approximately 1/3 keyboard work and 2/3 mouse operation. The order of different computer tasks presented to participants was randomized within each 45-minute session.

Prior to the experiment, participants were trained on two topics: how to operate the workstation adjustment and fundamental ergonomics workstation principles. The workstation adjustments were demonstrated by the experimenter and participants were encouraged to make as many adjustments as they saw necessary to determine their most comfortable workstation set up. The ergonomic training was very general covering fundamental ergonomic workstation principles consisted of describing visual access, reach, and support. No specific example regarding how to set up computer workstations was provided.

Workstation and User position measurements

A 3-D motion analysis system (Optotrak Certus, Northern Digital, Ontario, Canada) recorded the position of the workstation components (desk height, keyboard, mouse, and monitor). Infrared light-emitting diodes (IRLEDs) were placed on each component to track the positions of all components real time. The mouse marker was place at the front tip of the mouse. The keyboard marker was placed at the front edge midpoint of the keyboard close to function keys “F5” and “F6.” Three markers were attached together to form a rigid body and placed on the monitor to track both the angle and position of the device.

Groups of three ILEDs formed rigid bodies and were placed on user's head, torso, and upper arm to track the positions of key landmarks of the user, including the midpoint of user's eyes, sternum and elbow, respectively. The reference point (also used as the origin for the 3-D motion tracking system coordinate) was chosen as the front edge mid-point of the desk. Upon completion of the protocol, the users were asked to have two reference postures recorded used for analyses, one for sitting and one for standing. For such a reference posture, the participants were asked to sit up or stand up straight with eye sight parallel to the floor. The participants were asked to stand or sit at a distance where their hands and only their hands were just above the desk, while relaxing their shoulder and upper arms, and maintaining their upper arm and forearm at a 90 degree angle.

The final preferred position for the user was considered to be the final minute of each of the four 45-minute sessions. The final minute was chosen for each session because we expected that participants would settle into a similar configuration over time and the settings towards the end of the session would be representative of user's final preferred configuration. In addition, each session was parsed into four 11.25-minute segments based on the experimenter's interruptions. The position data relative to the user for the final minute of each four 11.25-minute segment was analyzed to evaluate the representativeness of the final minute of the workstation component position (for the entire 45-minute session) compared to different time points throughout each 45-minute session.

To ensure that the psychophysical protocol worked, that is the position of the devices converge and were reliable, we examined the position data trend to ensure that there was no linearity and we also confirmed that the magnitude of the workstation adjustments decreased as the sessions progressed. Specifically, the four final-minute location data points within each session were plotted and modeled via linear regression analysis to assess the data for evidence of either linearity within each participant or linearity across the entire sample population. A clear upward or downward trend of the scatter plots across or within participants for the four data points would signify a certain bias of the protocol and correspond to lower reliability of the overall results. In order to evaluate convergence of measurements even in the absence of a linear trend and to understand overall patterns of variability, a second analysis was conducted. Here the three absolute values were computed of the differences between the four sequential segments (e.g. segment 4 minus segment 3, segment 3 minus segment 2 and segment 2 minus segment 1) of final location data (the 1 minute averages) to investigate patterns of variability over time in participants' adjustments throughout each session. A decrease in the absolute value of the position data differences as the session progresses would signify that participants' perception of most comfortable location was converging to the final location indicated by the final minute of each 45-minute session. The data trend analysis for data with reference to user's stationary reference posture was not performed since the data trend would be identical to data with reference to the stationary desk origin as both data sets essentially present the same absolute position with respect to a stationary reference point.

Data and Statistical Analysis

For all dependent variables, marginal means and standard errors were calculated and used as the outcome measure for each 45-minute session. Variation for each outcome measure for both sitting and standing was modeled using repeated measures analysis of variance (RM-ANOVA), with participant included as a random effect. Session (first time versus second time using the workstation) and Workstation (sitting versus standing) and their potential interaction were evaluated in each model. Significance criteria (alpha values) were set at 0.05, two-sided. When a significant effect was found, a post-hoc analysis with Tukey's honestly significant test was conducted across the two workstations, two sessions and four segments. Statistical analysis was performed using JMP Pro 11 (SAS) linear mixed model module software.

Results

The selected computer workstation setup with respect to both the desk and the user for standing was found to be significantly different from that for sitting (Tables 1.2a and 1.2b). All participants reported similar setup locations during the first and the second session except for the forward mouse location. No interaction was significant between workstation (sitting/standing) and sequence (first time/second time). Subsequent trend analyses for the study protocol revealed no linear trend of the workstation setup location data; and users were making smaller adjustments as the protocol progressed in the study.

Using the front edge midpoint of the desk as the reference point, users placed mouse further away (3cm forward) from the reference point for standing compared to sitting. Users also placed the keyboard further away (4cm forward) from the reference point for standing compared to sitting (Table 2a). The desk height was set 74cm above the floor when sitting and 98cm above the floor when standing. The top edge of the monitor display was set 45cm above the desk level when sitting and 51cm when standing (Table 2b).Based on user's reference posture, standing erect with their palms on the edge of the table, the user selected workstation set up between sitting and standing were similar for the mouse and keyboard. The mouse was placed 54cm in front of the sternum and between 31 to 33cm to the right of the sternum. The keyboard midpoint was placed between 56-57cm in front of the sternum and between 3 to 5cm to the right of the sternum (Table 1.2a). For sitting, users set up the monitor top edge 9 cm below their eye level when they sat up straight with a slight upward tilt of 8 degrees; whereas for standing, users set up the monitor with its top edge 13 cm below their eye level when they stood up straight with a greater upward tilt of 18 degrees (Table 1.2b). In addition, the Desk was a few centimeters below standing elbow height when standing compared to a few centimeters above when sitting.

Using user's real time sternum location as reference, the mouse and keyboard were 10-12 cm closer to their sternum for standing compared to sitting (Table 1.2a). Similar to the reference posture, the desk height was 4cm lower than their elbow height while standing but 4.4cm higher than their elbow while sitting (Table 1.2b). Compared to the real-time eye level, the monitor was 3cm lower than user's eye level while sitting, and 10cm lower than the eye level while standing (Table 1.2b).

Table 1.2a **Final Keyboard and Mouse Location (cm)** presented as across participant marginal means (and standard errors)

	Workstation			Sequence			Workstation x Sequence
	p-Value[1,2]	Sit	Stand	p-Value	First	Second	p-Value
MOUSE X (In front of)							
Desk edge	**0.0017**	25 (1) [B]	28 (1) [A]	0.66	26 (1)	27 (1)	0.99
Moving sternum	**<0.0001**	41 (1) [A]	30 (1) [B]	**0.01**	**32 (1)**	**38 (1)**	0.21
Reference sternum	0.71	54 (1)	54 (1)	0.67	54 (1)	54 (1)	0.99
MOUSE Y (Right of)							
Desk midpoint	0.38	25 (1)	25 (1)	0.95	25 (1)	25 (1)	0.91
Moving sternum	0.11	31 (1)	33(1)	0.24	32 (1)	33 (1)	0.45
Reference sternum	0.46	31 (1)	33 (1)	0.96	32 (1)	33 (1)	0.92
Keyboard X (In front)							
Desk edge	**<0.0001**	27(1)[B]	31(1)[A]	0.57	29 (1)	29 (1)	0.69
Moving sternum	**<0.0001**	42(2)[A]	33(2)[B]	0.69	37 (1)	34(1)	0.89
Reference sternum	0.24	56 (1)	57(1)	0.61	56 (1)	56 (1)	0.72
Keyboard Y (Right of)							
Desk midpoint	**<0.0001**	-3(1)[B]	5(1)[A]	0.46	1 (1)	1 (1)	0.55
Moving sternum	0.058	3(1)	5(1)	0.35	5 (1)	4 (1)	0.54
Reference sternum	**<0.0001**	3(1)[B]	5(1)[A]	0.58	5 (1)	4 (1)	0.65

*Note: Distance from front center front edge to back edge is 12cm, to 'g' and 'h' key is 6.5cm. Dimension of the keyboard is 28.5x12cm

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, fixed effects Workstation (2 levels), Session (2 levels) and their interaction. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B. Values with the same superscript letters indicate no significant difference.

Table 1.2b **Final Desk and Monitor Location** presented as across participant marginal means (and standard errors)

	Workstation			Sequence			Workstation x Seque
	p-Value[1,2]	Sit	Stand	p-Value	First	Second	p-Value
Desk Height (above)							
Floor (cm)	**<0.0001**	74(10)	98(10)	0.96	84 (10)	84 (10)	0.48
Moving Elbow	**<0.0001**	$4(1)^{A}$	$-4(1)^{B}$	0.77	0 (1)	5 (1)	0.76
Reference Elbow	**<0.0001**	$3(1)^{A}$	$-5(1)^{B}$	0.87	-1 (1)	4 (1)	0.49
Monitor Height (above)							
Desk level(cm)	**0.0001**	45(13)	51(13)	0.81	48 (13)	47 (13)	0.17
Moving Eye Level	**0.0400**	$-3(3)^{A}$	$-10(3)^{B}$	0.88	-6 (3)	-7 (3)	0.46
Reference Eye Level	**0.0001**	-9(3)	-13(3)	0.81	-10 (3)	-11(3)	0.16
Monitor Angle (°)	**<0.0001**	$8(1)^{B}$	$18(1)^{A}$	0.87	13 (1)	13 (1)	0.95

*Note: Distance from front center front edge to back edge is 12cm, to 'g' and 'h' key is 6.5cm. Dimension of the keyboard is 28.5x12cm

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, fixed effects Workstation (2 levels), Session (2 levels) and their interaction. Bold values indicate a significant effect (p<0.05).

[2]For significant main effects, Tukey's Post-Hoc groupings are ranked such that A>B. Values with the same superscript letters indicate no significant difference.

Linear trend test of position change over time within each 45-minute session (4-Segment linear trend inspection)

During sitting workstation sessions, no linear trend for the four segment data points was observed for any outcome measure (Table 1.3a). In addition, no interaction between session and segment was identified. For most outcome measures, after allowing for the main effects in the model, more than 60% of the remaining error was attributable to participants, indicating that for these experiments a majority of variability was due to subject-to-subject differences.

Similarly for standing workstation sessions, no linear trend for the segment data points was observed for any outcome measure (Table 1.3b) and no interaction between session and segment was found. The percentage error attributable to participants ranged from 37 to 79 percent, also reflecting substantial subject-to-subject variation.

Position change difference over time within each 45-minute session (Absolute difference trend evaluation)

A downward or flat trend for the absolute value of the differences in location data between each adjacent segment was observed for almost all measures (Figure 1.2). Specifically, for the majority of the participants, the absolute value of the location difference between the final minute of the third segment and the second segment was smaller than the absolute difference value between second and the first. Similarly, for most of our participants, the absolute value of the difference between the final minute of the fourth (last) segment and the third segment was smaller than the absolute value of the difference between third and the second. With almost all participants having the smallest difference between the fourth and the third segment, this signifies that the participants had gradually converged, reaching the workstation setting he/she deemed most comfortable, and that the location of the final minute reported in Table 2a and 2b is representative of what the participants considered as his/her preferred location for specific workstation components during each session.

Table 1.3a: The effects of Session and Segment estimated from the linear regression relative to real time moving postures and desk origin for sitting workstation.

	Model			Error	
Position	Session difference test p-value*	Session mean first / second**	Segment data linearity test***	Percent variability attributable to participants	Percent variability attributable to error
MOUSE position (cm)					
In front of sternum	**<0.0001**	49 / 58	0.88	71%	29%
Right of the sternum	**<0.0001**	10 / 17	0.89	61%	39%
In front of desk origin	**0.001**	24 / 25	0.81	73%	27%
Right of desk origin	0.23	25 / 24	0.65	63%	37%
KEYBOARD position (cm)					
In front of sternum	0.31	43 / 42	0.51	70%	30%
Right of the sternum	0.67	3.6 / 3.4	0.95	71%	29%
In front of desk origin	0.09	26 / 27	0.84	69%	31%
Right of the desk origin	**0.04**	2.6 / 3.3	0.96	59%	41%
DESK height (cm)					
compared to elbow	**0.04**	4.4 / 5.3	0.22	65%	35%
compared to floor	**0.01**	84 / 76	0.58	94%	6%
MONITOR height (cm)					
compared to eye level	0.15	3.5 / 2.0	0.61	74%	26%
compared to desk origin	0.22	42 / 47	0.83	73%	27%
Monitor Angle (°)	0.73	8 / 8	0.73	76%	24%

* Session (2 levels) denotes the first or second time the participant works with the sitting computer workstation in the study. Detection of significance here indicates that the trend for the two sessions were significantly different

** The session means presented here are different from Table 2a and 2b as data here reflects the mean of the all four segments; whereas, only the final segment data point was used for Table 2a and 2b

***Segment (4 levels) denotes the 4 final-minute location data prior to session interruption while working with the sitting computer workstation in the study for each 11 ¼ minute segment. Detection of significance here indicates a clear linear trend of the four segment data points, which would suggest bias in the study protocol.

Table 1.3b: The effects of Session and Segment estimated from the linear regression relative to real time moving postures and desk origin for standing workstation.

Position	Model: Session difference test p-value*	Model: Session mean first / second**	Model: Segment data linearity test***	Error: Percent variability attributable to participants	Error: Percent variability attributable to error
MOUSE position (cm)					
In front of sternum	0.78	25 / 24	0.69	46%	54%
Right of the sternum	**<0.0001**	42 / 26	0.71	63%	37%
In front of desk origin	**0.0085**	25 / 24	0.75	47%	53%
Right of desk origin	0.54	26 / 26	0.44	67%	33%
KEYBOARD position (cm)					
In front of sternum	0.19	43 / 44	0.79	37%	63%
Right of the sternum	0.74	4.8 / 4.7	0.38	79%	21%
In front of desk origin	0.12	27 / 29	0.33	32%	68%
Right of the desk origin	0.35	2 / 3	0.54	76%	24%
DESK height (cm)					
compared to elbow	**0.04**	-4.7 / -3.8	0.80	78%	22%
compared to floor	0.09	98 / 101	0.57	93%	7%
MONITOR height (cm)					
compared to eye level	0.33	11 / 13	0.38	47%	53%
compared to desk origin	0.18	50 / 53	0.28	60%	40%
Monitor Angle (°)	0.67	17 / 17	0.86	73%	27%

* Session (2 levels) denotes the first or second time the participant works with the sitting computer workstation in the study. Detection of significance here indicates that the "shape" of the trend for the two sessions were significantly different

** The session means presented here are different from Table 2a and 2b as data here reflects the mean of the all four segments; whereas, only the final segment data point was used for Table 2a and 2b

***Segment (4 levels) denotes the 4 final-minute location data prior to workstation interruption while working with the sitting computer workstation in the study. Detection of significance here indicates there is a clear linear trend of the four segment data points, which would suggest bias in the study protocol.

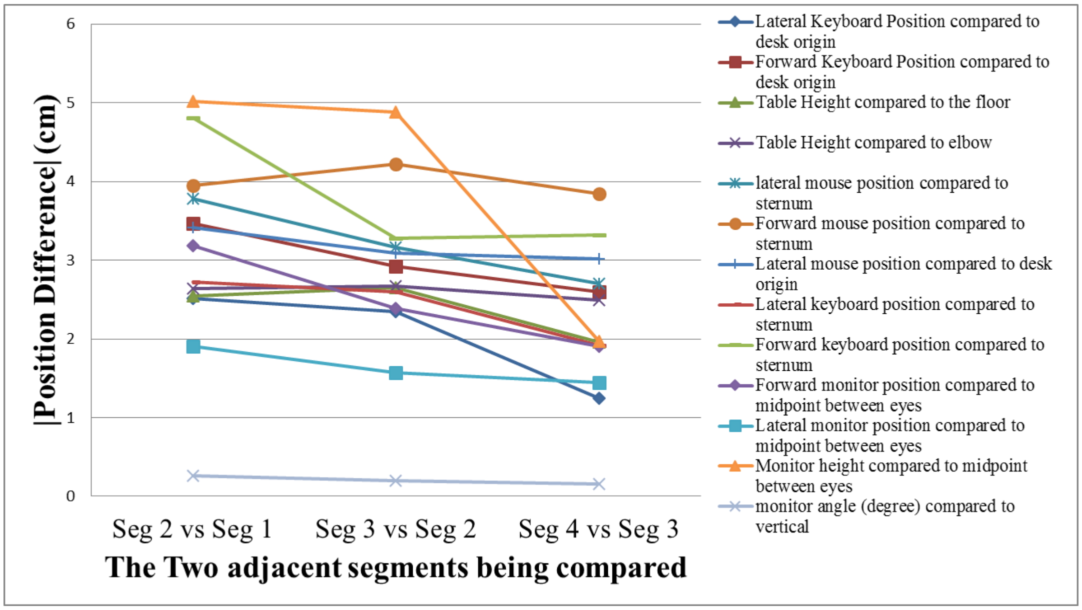

Figure 1.2a: Absolute difference trend evaluation for position of the last 1 minute between the four sequential 11¼ minute segments for standing computer workstation. Across participant mean values, with respect to the moving posture and stationary desk origin are presented. The X-axis signifies the two sequential segments being compared, including the first segment and the second, the second segment with the third, and the third segment with the fourth, respectively. A flat or downward trend indicates that participants had or were still converging on a final range of values for their preferred set up.

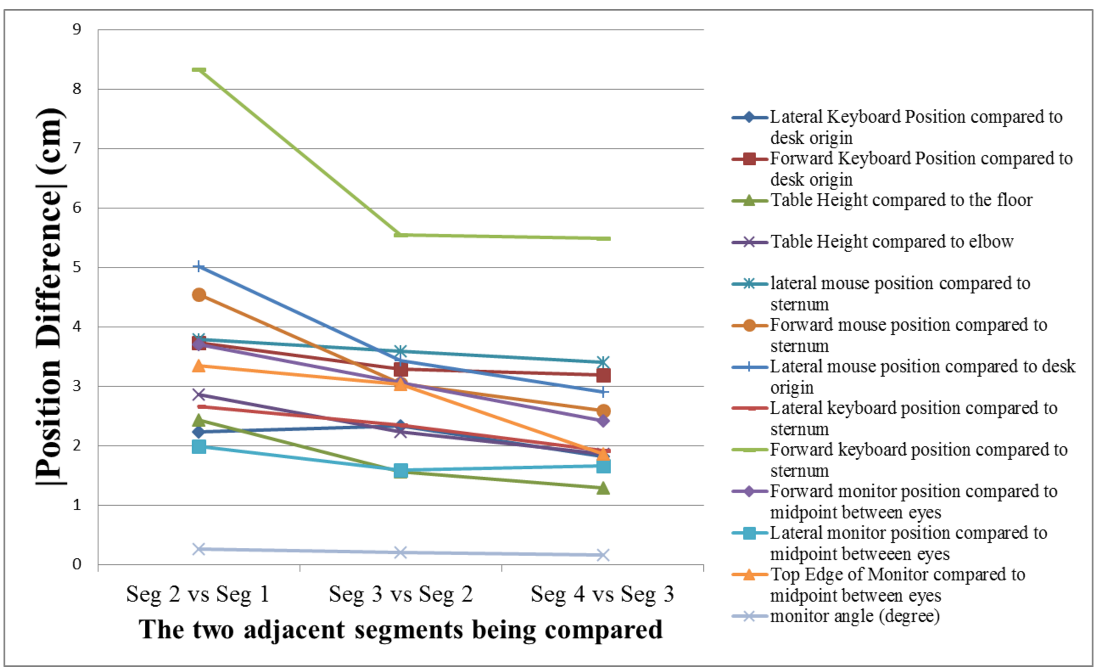

Figure 1.2b: Absolute difference trend evaluation for position of the last 1 minute between the four sequential 11¼ minute segments for sitting computer workstation. Across participant mean values in reference to moving posture and stationary desk origin are presented.

Discussion

The goal of this study was to determine the users' preferred setup for both sitting and standing computer workstations through identifying their self-selected configuration during a psychophysical protocol. Consistent with our hypothesis, the results indicate that the selected setup for standing workstation was different from that for sitting workstation. Specifically, users placed both mouse and keyboard further away from the front edge of the desk. However, both mouse and keyboard were actually placed closer to users' body (sternum) while standing compared to sitting. In addition, users selected a lower desk height with respect to their elbow for standing compared to sitting. The display was set up to be lower than users' eye level with a greater upward tilt for standing than sitting.

The data suggest that the difference between the sitting and the standing may be related to the back support afforded to the user for the sitting workstation compared to the standing workstation. By seeking support from the chair back while sitting and the desk while standing, the user's head and torso were consistently at a lower height compared to when they sat and stood straight up. Such an observation was evident in our findings while comparing the final workstation set up with both the reference posture set up by the experimenter and the real-time captured posture adopted by the users while actually using the workstation (Table 1.2a). Therefore, when setting up comfortable computer workstations, in particular for a standing computer workstation, the key first step for the users may be to take into account how they plan to support their torso, thus to keep in mind that they may eventually stand closer to the desk for support, and then arrange the computer workstation components accordingly.

The self-selected positions fell within the large range of workstation recommendations available. In comparison with OSHA (and the identical ANSI/HFES 100) recommended workstation setup, the viewing distance for standing workstation was found to be slightly closer at 64cm but still falls within the OSHA recommended range of 50 to 100 cm. Additionally, the final selected setup for sitting computer workstation was similar to the OSHA recommendations, specifically with the "Reclined sitting" neutral body positioning suggested in the eTool provided on the OSHA website. The workstation setup results for standing computer workstation was also in line with the setup illustrated by OSHA for neutral “Standing” provided in the same online tool designed to help office workers design their computer workstations. By comparing the relative location of the devices in the illustrations between the “Reclined sitting” and “Standing,” it is clear that the major findings regarding the workstation setup in the current study are consistent with what are currently implied in the OSHA website illustrations (OSHA, n.d.; ANSI/HFES 100, 2007).

The self-selected positions are also in line with previous research. The selected keyboard distance from keyboard home row (‘j’ key) to desk front edge for sitting (21.5cm) and standing (25.5cm) corresponded with Marcus et al.’s research that associated with lower risk hand/arm MSDs (Marcus, 2002).The average viewing distance of the monitor display at 70cm for sitting computer workstation was similar to Shin and Hegde’s work that looked at the user-preferred position of computer display which they found the preferred distance to be 68cm for a 19-inch display (Shin and Hegde, 2010). The monitor angle findings in the current study may help provide guideline recommendations as the viewing angles of computer monitors were found to affect user’s neck posture, overall comfort, and neck and low back comfort levels (Young, 2012; Kothiyal and Bjornerem, 2009). The 18^{o} viewing angle of the monitor for standing workstation was similar to what is suggested (17^{o}) in previous literature and ANSI/HFES 100 (Burgess-Limerick et al, 2000; ANSI/HFES 100, 2007).

The novelty of our approach for the multiple parameters associated with a computer workstation may have pushed the limits of typical psychosocial protocols; however, the data suggest that the protocol appears to be robust. With a standardized training procedure and script, most participants were able to come to similar final setup position between their two sessions for each standing and sitting workstation. Additionally, after synthesizing the results from the 4-segment linear trend and absolute difference trend analyses for each of the participant’s 45-minute session, it was clear that progressively, participants were experimenting with their workstation setup and gradually converging to the workstation they perceived as most comfortable. Thus, the two trend evaluations showed that indeed the participants’ ideas of comfortable computer workstation setup do vary initially, but could gradually reach a final preferred setup.

Furthermore, the large proportion of ANOVA model error attributable to participants indicates that our repeated measures protocol worked effectively to overcome between-subject variability. It also indicates that while each person may experiment with their sitting or standing workstation setup initially, the protocol allowed enough time for the users to reach a steady-state setup. By repeating each sitting and standing condition, the reproducibility and effectiveness of the protocol were also demonstrated. Therefore, we believe the final location results with respect to user's body frame are representative of participants' perceived comfortable setup for sitting and standing. Additionally, the current study demonstrates the importance of reasonable duration in order to allow the positioning data to reach convergence within a session.

The final selected set up for both sitting and standing workstations varied largely across the users. This variability suggests that users found different solutions afforded by the multi-component system. Therefore, future computer workstation set up guidelines should consider providing a range of recommended set up to allow adjustability, while emphasizing adequate ergonomic trainings for work-related MSD prevention (Robertson, 2013).

Through the current study results, we believe this is a good initial step towards recommendations for establishing ergonomic guidelines to set up adjustable standing computer workstations. Future studies may consider having longer session length to better simulate longer work hours and allow more time for the final workstation location data to converge. Additionally, the current study protocol can be further improved by adding psychological stress and performance measures to further investigate the relationships between work station setup, task performance, and work stress. Comparisons of biomechanics between the two preferred workstation set ups will also provide valuable insights into how postures, muscle loads and perceived comfort are affected by these user-selected workstation set ups.

The study conclusions need to be considered within its limitations. First, our psychophysical protocol asks users to adjust multiple parameters all at once, unlike methods used to develop ergonomic lifting guidelines where usually only a single parameter was adjusted during a protocol. However, the multiple adjustments are typical of real world settings and requirements of users. Also, our study task output was inconsequential to the users, which may have contributed to why the reclined sitting posture was favored over the more engaged upright posture (OSHA). The generalizability of the study results may be limited to young professionals that fall around the same age range of the study population as we recruited participants between 21 and 40 years of age to avoid the effect of presbyopia causing workstation setup discrepancies. Ultimately, we believe that while this was a small pilot study, the information gathered is an important step towards deriving recommendations and eventual guidelines for computer workers to utilize standing workstations safely and productively, maximizing their beneficial health effects while minimizing musculoskeletal complaints and, ultimately, to reduce injury.

Conclusions

Overall, the study demonstrates that, despite the similarity in components, a standing computer workstation may warrant a different set of guidelines for its setup compared to a sitting computer workstation. A key to comfortable setups may be to provide adjustability to accommodate users' perception of comfort to suit individual needs. The current findings also suggest that psychophysical protocol could be an effective tool to provide insights on users' perceived comfortable setting while working with a particular workstation setup. For future studies, users' biomechanical loads, including postures, muscle efforts and comfort level associated with working with their perceived comfortable workstations should be investigated.

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Chapter 2

Evaluating Biomechanics of User-Selected Sitting and Standing Computer Workstation

Abstract

A standing computer workstation has now become a popular modern work place intervention to reduce sedentary behavior at work. However, user's biomechanical loads related to a standing computer workstation and its differences with a sitting workstation need to be understood to understand the postural variability that results and also to assist in developing recommendations for use and set up. We compared the difference in upper extremity biomechanical loads between user-selected sitting and standing workstation setups. Twenty participants (10 females, 10 males) volunteered for the study. We measured 3-D posture, surface electromyography, and user-reported discomfort, while completing simulated tasks with each participant's self-selected workstation setups. Sitting computer workstation associated with more non-neutral shoulder postures and greater shoulder muscle load, while standing computer workstation induced greater wrist adduction angle and greater extensor carpi radialis muscle activity. Sitting computer workstation also associated with greater shoulder abduction postural variability (90^{th} – 10^{th} percentile) while standing computer workstation associated with greater variability for should rotation and wrist extension. Users reported similar overall discomfort levels within the first 10 minutes of work but had more than twice as much discomfort while standing than sitting after 45 minutes; with most discomfort reported in the low back for standing and shoulder for sitting. These different biomechanical loads provide variance in posture and musculoskeletal loading between sitting and standing and by alternating between the two configurations in short bouts may be a way of changing the mechanical load on the upper extremity.

Key Words: Office work, Workstation, Musculoskeletal Disorders

Introduction

In modern days, the North American population spends more than 55% of their waking hours being sedentary (Colley et al., 2011; Matthews et al., 2008). As sedentary lifestyle associated with prolonged sitting has been connected with increased risk of multiple adverse health outcomes including obesity, diabetes mellitus and cardio vascular mortality (Dunstan et al., 2010; Ryan et al., 2011; Thorp et al., 2012, Smith et al., 1999), one current popular workplace response has been to adopt more standing to replace sitting at work. Specifically, a standing workstation has now become a popular modern work place intervention to reduce sedentary behavior at work. However, both sitting and standing workstations present risk of musculoskeletal disorders (MSDs).

Many studies documented potential adverse health outcomes associated with seated computer work. A previous study has shown that users who perform long hours of computer work can develop long term fatigue in their hands and arms (Lin, 2004). A separate study of 203 workers who averaged eight hours of seated computer work per day also found MSD incidence rates at 73% in shoulder, 71% in neck and 60% in upper back (Cho et al. 2012). Major office MSD risk factors include non-neutral postures (extreme shoulder abduction, forearm pronation, ulnar deviation and wrist extension) and sustained muscle loads (Houwink et al, 2009; Burgess-Limerick, 1999; Jensen, 1998; Karlqvist, 1998; Sjøgaard, 1998), which are closely related to workstation set up such as equipment positioning (Psihogios, 1998; Sommerich, 2000).

Specific placement and arrangement of a computer workstation have been evaluated to determine the effects on upper extremity biomechanics (Burgess-Limerick, 1999, Dennerlein, 2006, Jensen, 1998). However, different workstation set ups and their impact on the variability of user's upper extremity posture and muscle activity remain unclear. Motor variability is found to associate with delaying or alleviating fatigue, and potentially lowering MSD risks (Srinivasan, 2012).

Comparing to sitting, a standing workstation removes the task chair and requires users to find alternative ways of arm and body support (Taillefer et al., 2011, Marshall et al., 2011; NelsonWong et al., 2010). Thus, a standing workstation may afford users to change their postures and muscle loading patterns more frequently while seeking support, compared to a sitting workstation. Therefore, understanding the biomechanical loads and motor variability related with sitting and standing workstations may help determine the associations between workstation set ups, user-perceived discomfort, and potential MSD risks.

The primary objective of this study is to evaluate the biomechanical loads and motor variability of both sitting and standing workstations based on users' preferred workstation set up. As part of a psychophysical workstation protocol, where users self-selected their desk height, keyboard, mouse, and monitor positions (Lin et al, 2015) we measured users' biomechanical while they were sitting and standing. Due to the lack of support in standing, we hypothesize that postures and muscle loads associated with a sitting computer workstation will differ from a standing computer workstation. We also hypothesize that this reduction in support during standing will be associated with greater postural variability and dynamic muscle activity compared to the sitting workstation.

Methods

Twenty adult right-handed participants (10 males and 10 females) with no history of neck or upper extremity musculoskeletal injuries or pain volunteered and provided written informed consent for the repeated measure laboratory study. Participants' mean anthropometric measures were typical of the average United States population (Table 2.1). All protocols and informed consent forms were approved by Northeastern University Human Subject Research Protection. The 3-hour study protocol consisted of four 45-minute sessions alternating between standing and sitting; the order of standing and sitting was balanced across participants. During each 45-minute session, the participants were asked to complete a set of typical computer tasks involving both keyboard and mouse work.

	Males (N=10)	Females (N=10)	All
Age (yrs)	29 (5)	26(5)	27.4 (5)
Height (cm)	179 (6)	164 (5)	171 (9)
Weight (kg)	81 (18)	61 (11)	71 (18)
Hand Length (cm)	19 (0.9)	18 (0.6)	18 (1.1)
Hand breadth (cm)	9.6 (0.6)	8.3 (0.4)	9 (1)
Shoulder width (cm)	44 (3)	40 (2)	42 (3)
Forearm length (cm)	46 (2)	41 (2)	44 (3)
Chair height (cm)	49 (2)	47 (1)	48 (2)

Table 2.1: Anthropometric measures of means (standard deviations) across all participants

The data for this study were collected as part of psychophysical protocol where participants self-selected their workstation with the instruction to adjust the workstation to a point where they find the workstation to be comfortable over four 45 minute periods (Lin et al, 2015). The four periods alternated between sitting and standing at a highly adjustable workstation with the first period assignment to sitting or standing was randomized and counterbalanced across participants. The final workstation set ups selected by the users through this psychophysical protocol are provided in table 2.2.

All participants' activities and interactions with the workstation were recorded real time continuously using 3-D motion analysis and surface electromyography. The 10^{th} percentile, median and 90^{th} percentile values of user's posture and muscle effort data were calculated for each of the four 45 minute periods. In addition, after each period, participants provided feedback on their discomfort level using a standardized survey questionnaire.

Workstation Conditions and Experiment Protocol and Tasks

Each participant completed a series of standardized computer tasks four times, during each of the four 45 minute bouts alternating between sitting and standing for each bout. All participants used the same sit-stand workstation consisted of a height-adjustable table (Airtouch®, Steelcase), a wireless mouse (M325®, Logitech), a wireless keyboard (Slim Bluetooth keyboard, Hewlett-Packard), and a 19-inch LCD monitor (DELL) supported with an easy-to-adjust mechanical arm (LX Desk Mount LCD Arm, Ergotron). For all workstation conditions, a chair without arm rest (Ergonomic Task Chair, casted by Superior Furniture, TX) was provided to the participant with the chair height adjusted by the experimenter such that the participant's feet remained on the floor and the thighs were parallel with the floor throughout the experiment.

Each 45 minute bout was parsed into four 11.25-minute segments. At the end of each segment, the experimenter interrupted the user and reset the workstation to one of several extreme positions. The participant had to readjust the height of the desk, the position of the keyboard and mouse, and the three-dimensional position and angle of the monitor to her/his preferred working locations. All participants performed four customized office tasks: answering emails, constructing an excel spreadsheets, editing essays and playing simple pattern-matching games. The tasks simulated daily office work activity that may involve transcribing texts, completing Internet research, data entry, writing small correspondences, and casual gaming. The overall task completion required approximately 1/3 of keyboard work and 2/3 of mouse operation. The order of different computer tasks presented to participants was randomized within each 45-minute bout.

Dependent Variables: Posture

An optical three-dimensional motion analysis system (Optotrak Certus, Northern Digital, Ontario, Canada) recorded upper limb posture. Three infrared light-emitting diodes (IRLEDs) were mounted on to a rigid body clusters consisting of three IRLEDs attached to a metal structure attached to the dorsal side of the hand over the 3rd metacarpal bone between the wrist and knuckle. Three additional rigid bodies were attached to the forearm, upper arm, head and chest. Locations of bony landmarks (right and left temple, midpoint between eyes, right and left acromion, sternal notch, lateral and medial epicondyle of the right elbow, radial and ulnar styloid of the right wrist, metacarpophalangeal joints for digits II-IV of the right hand) were palpated, digitized and tracked according to their corresponding body segment IRLED cluster. Location data for each IRLED and digitized point were subsequently filtered through a low-pass, fourth-order Butterworth filter with a 10 Hz cutoff frequency and used to define local coordinate systems for each segment (Asundi et al., 2010, Asundi et al., 2012, Winter, 2005).

Using the anatomical position as reference, joint angles were defined by the rotation matrices describing the orientation of the distal segment relative to the proximal segment. Specifically, from the local coordinate systems, rotation matrices were calculated to obtain the neck orientation relative to vertical axis, the torso orientation relative to the neck, upper arm orientation relative to the torso, the forearm relative to the upper arm, and the hand/wrist orientation relative to the forearm. With these local rotation matrices, Euler angles for all body segments of interest were calculated to describe flexion, extension, abduction, adduction, and rotation (internal or external) of the right shoulder, elbow, and wrist (Asundi et al., 2010, Asundi et al., 2012, Winter, 2005).

At the end of the study protocol, two reference postures, one for sitting and one for standing workstation, were captured for each participant. For the standing workstation, the participants were asked to stand at where they were at without moving their feet, and stand straight up with shoulders relaxed and looking directly forward. The table height was adjusted to participants' resting elbow height while standing and they were asked to keep their elbow at a 90-degree angle when the reference posture was recorded. For sitting workstation, the participants were asked to stop working and without moving their chair asked to sit up straight with their shoulder relaxed and looking directly forward. The table height was adjusted to participants' resting elbow height while sitting and they were asked to keep their elbow at a 90-degree angle when the reference posture was recorded. The reference postures were used as the reference for changes away from this posture as the dependent measure for posture measurements in the study. The same reference postures and participants' positions with respect to the desk origin are used to present the self-selected workstation set up (Table 2.2). The median angle as well as the variability (defined as the 90^{th} minus 10^{th} percentile) of the continuous measures of the upper extremity posture were calculated as dependent measures for each trial.

	Workstation*	
	Sit	Stand
MOUSE X (In front of)		
Reference Sternum	54 (1)	54 (1)
MOUSE Y (Right of)		
Reference Sternum	31 (1)	33 (1)
Keyboard X (In front)		
Reference Sternum	56 (1)	57 (1)
Keyboard Y (Right of)		
Reference Sternum	3 (1)	5 (1)
Table Height (above)		
Reference Elbow	3 (1)	-5 (1)
Monitor Height (above)		
Reference Eye Level	-9 (3)	-13 (3)
Monitor Angle (°)	8 (1)	18 (1)

*Note: Distance from front center front edge to back edge is 120mm, to 'g' and 'h' key is 65mm. Dimension of the keyboard is 285x120mm

Table 2 **Final Device Location**: Across participant marginal means and standard errors

Dependent Variables: Muscle Activity

Surface electromyographic activity (EMG) of three shoulder muscles (anterior deltoid (AD), middle deltoid (MD), middle trapezius (MT), and upper trapezius (UT)) and muscle of the forearm (extensor carpi radialis (ECR)) were measured for the both sides of the body. Surface electrode pairs (Blue Sensor N, Ambu,Inc., Glen Burnie, MD) were spaced approximately 20mm apart and located over muscle bellies. The electrodes were placed in standard locations as defined by Perotto (Perotto, 1994). Placement of the electrode on the muscles was validated through palpation and signal response to targeted muscle contractions.

All EMG signals were amplified and recorded by a wireless biosignal data-logging system (Mega WBA, Mega Electronics, Ltd., Kuopio, Finland) at a frequency of 1000 Hz. The signals were then rectified, and smoothed using a 3 Hz low pass filter. To normalize results across participants, three 3-second isometric maximum voluntary contractions (MVC) were collected for each muscle with corresponding exercises. Participants were coached to gradually ramp up to reach an MVC by the experimenter while the experimenter resisted participants' force exertions using up to their entire bodyweight. Participants rested for two minutes between muscle contractions. The maximum voltage value obtained during any of the three contractions was used as to normalize the EMG signal and expressed as percent MVC of each muscle. The median amplitude as well as the 10^{th} and 90^{th} percentile of the continuous measures of the eight muscle activities were calculated as dependent measures for each trial.

Dependent Variables: User Perception

All participants responded to six survey questions about overall upper extremity discomfort level for the first ten minutes and for the entire 45-minute session with each specific workstation configuration (sitting or standing). The responses were marked on a 10-cm visual analogue scale (VAS) with 0 being the lowest level of discomfort and 10 being the highest. The participants were also asked to identify the preferred workstation setting and how long they thought they could have worked in a specific setting free of discomfort between 0 to 480 minutes in an eight-hour workday.

Data and Statistical Analysis

For all dependent variables, including posture (in angles), muscle activity (in percentage MVC), and user perception (VAS scale from 0 to 10), marginal means and standard errors were calculated and used as the outcome measure for each 45-minute session. Variation for each outcome measure across the two workstation conditions (sitting/standing) and two sessions (first/second) was tested using repeated measures analysis of variance (RM-ANOVA), with participant included as a random effect. Interaction between workstation and session was included in the model. Significance criteria (alpha value) were set at 0.05. When a significant effect was found, a student's t-test was conducted across the two workstations and two sessions. Statistical analysis was performed using JMP Pro 11 (SAS) linear mixed model module software.

Results

Posture

The standing computer workstation was associated with smaller shoulder abduction, shoulder flexion and shoulder external rotation, compared to sitting (Table 2.3a). While elbow flexion and forearm supination was not significantly different, users had greater wrist extension for standing compared to sitting. Users were also found to have greater neck extension (chin tilt) while sitting and greater torso extension compared to standing.

While using the standing computer workstation, participants had significantly greater joint excursions (90^{th} – 10^{th} percentile) for shoulder external rotation and wrist extension, compared to sitting. Shoulder abduction range was greater when participants were sitting compared to standing.

Table 2.3a: Upper Limb Posture: Across participant marginal means and standard errors for RMANOVA Workstation, Sequence, and their Interaction

	Workstation			Sequence			Condition x Task Interaction
Angle (°)	P-Value[1,2]	Sit	Stand	P-Value	First	Second	P-Value
Shoulder Abduction	**0.0004**	10.5 (1.8)[A]	5.6 (1.8)[B]	0.84	8(2)	8(2)	0.41
Shoulder Flexion	**<0.0001**	18.8 (2.2)[A]	4.9 (2.2)[B]	**0.028**	14(2.6)	10(2.6)	0.79
Shoulder External Rotation	**<0.0268**	17.2 (4.7)[A]	7.2(4.7)[B]	0.44	11(5)	12(5)	0.83
Elbow Extension	0.27	16.7 (3.9)	11.2(3.9)	0.29	11(4)	14(4)	0.07
Forearm Supination	0.43	0.4 (4)	4.3(4)	**0.001**	11(4) [A]	6(4)[B]	0.05
Wrist Adduction	0.57	10 (4)	12(4)	0.79	11(4)	10(4)	0.54
Wrist Extension	**0.04**	16 (5)[B]	24(5)[A]	0.89	8(5)	8(5)	0.22
Neck Right Bending	0.85	1 (1)	1(1)	0.05	2(1)	0(1)	0.16
Neck Extension (tilt)	**0.019**	4.2 (2)[A]	-1(2)[B]	0.69	2(2)	1(2)	0.42
Neck Twist	0.84	-1 (1)	-1(1)	0.83	-1(1)	-1(1)	0.83
Torso Flexion	0.055	-3 (3)	4 (3)	0.74	1 (3)	1 (3)	0.84

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Workstation (2 levels), Sequence (2 levels) and their interaction. Bold values indicate a significant effect (p<0.05).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B.

Table 2.3b: Upper Limb Posture Variability: Across participant marginal means and standard errors for RMANOVA Workstation, Sequence, and their Interaction

	Workstation			Sequence			Workstation x Sequence Interaction
Angle (°)	P-Value[1,2]	Sit	Stand	P-Value	First	Second	P-Value
Shoulder Abduction	**<0.0001**	**10 (1)[A]**	**5.8 (1)[B]**	0.15	9 (1)	8 (1)	0.75
Shoulder Flexion	0.46	8 (1)	7 (1)	0.84	7(1)	7(1)	0.89
Shoulder External Rotation	**0.018**	**10 (1)[B]**	**13 (1)[A]**	0.42	12(1)	12(1)	0.93
Elbow Extension	0.07	21(2)	15 (2)	0.38	19(2)	18(2)	0.24
Forearm Supination	0.09	4 (1)	7 (1)	0.33	5(1)	6(1)	0.33
Wrist Adduction	0.36	10 (2)	13(2)	0.73	11(2)	11(2)	0.73
Wrist Extension	**0.03**	**7 (1)[B]**	**11 (1)[A]**	0.91	8 (1)	9 (1)	0.52
Torso Flexion	0.07	3 (1)	5 (1)	0.34	4 (1)	4 (1)	0.55

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Workstation (2 levels), Sequence (2 levels) and their interaction. Bold values indicate a significant effect (p<0.05).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B.

Muscle Activity

The standing computer workstation associated with smaller shoulder muscle effort for middle trapezius and anterior deltoid on both left and right shoulders while also having smaller right middle deltoid load (Table 4a). In the forearm, users had greater right extensor carpi radialis muscle load for standing compared to sitting.

Similarly, while looking at the 10^{th} and 90^{th} percentile of the muscle activity, sitting computer workstation associated with greater right shoulder 10^{th} percentile load (middle trapezius and anterior deltoid) and greater right shoulder 90^{th} percentile load (middle deltoid), but lower right forearm muscle load (extensor carpi radialis) for both 10^{th} percentile and 90^{th} percentile (Table 4b and 4c).

User Perception

During the first 10 minutes of the 45-minute session, participants reported similar discomfort level for both sitting and standing. However, by the end of the 45-minute session, participants reported more than two times greater discomfort associated with standing compared to sitting (Table 5), with 65% of the participants referring the source of discomfort being the lower back. While being asked about how long they think they could work with each workstation without any discomfort, participants estimated that they could work almost three times as long when they are sitting (219 minutes) compared to when they are standing (86 minutes).

Table 2.4a: Median Muscle Activity: Across participant marginal means and standard errors for RMANOVA fixed effect Workstation, Sequence, and their Interaction

	Workstation			Sequence			Condition x Task Interaction
Median EMG activity (% MVC[3])	P-Value[1,2]	Sit	Stand	P-Value	First	Second	P-Value
Left Middle Trapizius	**<0.0001**	**3 (0.3)[A]**	**2.2 (0.3)[B]**	0.11	2.5(0.3)	2.7(0.3)	0.91
Left Anterior Deltoid	**<0.0015**	**0.9 (0.1)[A]**	**0.7 (0.1)[B]**	0.82	0.8(0.1)	0.8(0.1)	0.75
Left Middle Deltoid	0.37	1.2(0.1)	1.3(0.1)	0.14	1.3(0.1)	1.2(0.1)	0.64
Left Extensor Carpi Radialis	0.11	2.7(0.4)	3.0(0.4)	0.59	2.8(0.4)	3.0(0.4)	0.94
Right Middle Trapizius	**0.0021**	**2.9(0.4)[A]**	**2.3(0.4)[B]**	0.84	2.6(0.4)	2.6(0.4)	0.07
Right Anterior Deltoid	**<0.0001**	**1.1(0.1)[A]**	**0.9(0.1)[B]**	0.87	1.0(0.1)	1.0(0.1)	0.57
Right Middle Deltoid	**0.0005**	**1.1(0.1)[A]**	**0.9(0.1)[B]**	0.10	0.8(0.1)	0.8(0.1)	0.51
Right Extensor Carpi Radialis	**<0.0001**	**6.1(0.8)[B]**	**7.1(0.8)[A]**	0.43	6.5(1)	6.7(1)	0.60

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Workstation (2 levels), Sequence (2 levels) and their interaction. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B.

Table 2.4b: Tenth Percentile Muscle Activity: Across participant marginal means and standard errors for RMANOVA fixed effect Workstation, Sequence, and their Interaction

	Workstation			Sequence			Condition x Task Interaction
10th %ile EMG activity (% MVC[3])	P-Value[1,2]	Sit	Stand	P-Value	First	Second	P-Value
Left Middle Trapizius	0.72	2.4 (1)	1.9 (1)	0.33	2.1(1)	2.5(1)	0.25
Left Anterior Deltoid	0.51	0.6 (0)	0.6 (0)	0.10	0.6(0)	0.6(0)	0.61
Left Middle Deltoid	0.06	1.0(0.1)	1.1(0.1)	0.09	1.1(0.1)	1.1(0.1)	0.38
Left Extensor Carpi Radialis	0.70	1.9(0.3)	1.9(0.3)	0.67	1.9(0.3)	1.9(0.3)	0.051
Right Middle Trapizius	**0.0007**	**2.2(0.3)[A]**	**1.6(0.3)[B]**	0.56	1.8(0.3)	1.9(0.3)	0.99
Right Anterior Deltoid	**0.013**	**0.8(0.1)[A]**	**0.7(0.1)[B]**	0.31	0.7(0.1)	0.8(0.1)	0.84
Right Middle Deltoid	0.33	0.77(0.1)	0.72(0.1)	**0.036**	**0.79(0.1)[A]**	**0.69(0.1)[B]**	0.36
Right Extensor Carpi Radialis	**<0.0001**	**3.7(0.5)[B]**	**4.3(0.5)[A]**	0.59	4.0(0.5)	4.0(0.5)	0.81

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Workstation (2 levels), Sequence (2 levels) and their interaction. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B.

Table 2.4c: Ninetieth Percentile Muscle Activity: Across participant marginal means and standard errors for RMANOVA Workstation, Sequence, and their Interaction

	Workstation			Sequence			Condition x Task Interaction
90th %ile EMG activity (% MVC[3])	P-Value[1,2]	Sit	Stand	P-Value	First	Second	P-Value
Left Middle Trapizius	0.07	6.8 (1)	4.9 (1)	0.44	5.4(1)	6.2(1)	0.72
Left Anterior Deltoid	0.23	2.1 (0.3)	1.9 (0.3)	0.58	2.0(0.3)	2.1(0.3)	0.51
Left Middle Deltoid	0.55	2.0(0.3)	2.1(0.3)	0.20	2.2(0.3)	1.9(0.3)	0.97
Left Extensor Carpi Radialis	0.18	5.6(1)	6.2(1)	0.15	6.3(1)	5.5(1)	0.74
Right Middle Trapizius	0.08	6.9(1)	5.8(1)	0.32	6.0(1)	6.6(1)	0.40
Right Anterior Deltoid	0.33	3.1(1)	4.5(1)	0.33	3.1(1)	4.5(1)	0.34
Right Middle Deltoid	**0.0006**	**2.5(0.3)[A]**	**1.9 (0.3)[B]**	0.74	2.2(0.3)	2.1(0.3)	0.53
Right Extensor Carpi Radialis	**<0.0001**	**9.4(1)[B]**	**11(1)[A]**	0.56	10(1)	10(1)	0.99

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Workstation (2 levels), Sequence (2 levels) and their interaction. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Student's t-test groupings are ranked such that A>B.

Table 2.5: User Perception: Across participant marginal means and standard errors for RMANOVA from participant survey under each condition

User's Feedback	Workstation (VAS 10cm scale)		
	P-Value[1,2]	Sit	Stand
Discomfort (10 minutes)	0.06	0.9(0.3)	1.5(0.3)
Discomfort (45 minutes)	**<0.0001**	1.1(0.3)^{B}	2.7(0.3)^{A}
Projected Discomfort-free Time Estimate (minutes)	**<0.0001**	219(19)^{A}	86(19)^{B}

[1]One-way repeated measures ANOVA with participant as a random variable.

[2]For significant main effects, Student's t-test was performed to assess significant difference where A>B. Values with the same superscript letters indicate no significant difference.

Discussion

The goal of this study was to document differences in users' upper extremity posture and postural variability as well as muscle efforts and the range of this effort between using a sitting and a standing computer workstation. The findings were consistent with our hypothesis that the biomechanical loads including both posture and muscle activity of users' upper extremity differed between user-selected sitting and standing computer workstations. Specifically, sitting computer workstation associated with less neutral shoulder posture and greater shoulder muscle load, but smaller wrist extension angle and lower wrist extensor muscle activity. Our other hypothesis was partly supported by our findings. We found greater postural variability for wrist extension and shoulder rotation associated with standing, but greater shoulder abduction variability associated with sitting. We also found greater wrist EMG dynamic range associated with standing, but greater shoulder EMG dynamic range associated with sitting.

The differences in posture observed may be afforded by how the participants selected to set up their workstations relative to their body. With both the keyboard and the mouse placed closer to users' body (sternum) while standing, users were able to operate both the keyboard and the mouse with smaller shoulder abduction, flexion, and external rotation, compared to sitting. Consequently, shoulder muscle activity was generally lower for standing than sitting across the 10^{th}, 50^{th}, and 90^{th} percentiles. With table height lower than their elbow height while standing, users had greater wrist extension compared to sitting when the table was set slightly higher than their elbow height. Correspondingly, wrist extensor muscle activity (extensor carpi radialis) of the right hand was also greater when participants were standing compared to sitting. With the monitor set lower than their eye level, users while standing had less chin tilt compared to sitting when the monitor was at their eye level. Although not statistically significant, user's torso leaned forward a bit more with a slightly positive torso flexion angle while standing, compared to a slight negative torso flexion angle when users leaned backwards on the chair back while sitting.

The postures adopted by users associated with sitting and standing computer workstations resembled "Reclined sitting" and "Standing" ergonomic postures, respectively (OSHA, n.d.). The posture findings indicate that users while standing stood closer to the desk edge for body support, but leaned back and further away from the desk while sitting. Specifically for sitting, users leaned backward into the chair back for back support and transmitted more of the weight from the upper body to the floor (Huang et al, 2012). Such a reclined sitting posture adopted by users corresponded with results presented by Schüldt et al which found the reclined sitting posture with a slightly leaned back torso to be the most relaxing and associate with the least static shoulder muscle effort, when comparing four different seated postures (Schüldt et al, 1993). The current study results also agree with Kingma and van Dieën's findings regarding how computer users respond to the removal of the back support by either supporting their upper body weight with their spine or through leaning forward placing their forearms onto the desk (Kingma and van Dieën, 2009). The difference in neck postures was consistent with previous studies that related neck posture closely to the viewing angles of computer displays (Young, 2012; Kothiyal and Bjornerem, 2009). The elevated discomfort, specific in the low back region is consistent with previous reports that showed prolonged occupational standing to associate with elevated low back pain (LBP) and discomfort reporting (Roelen et al. 2008; Tissot, Messing, and Stock 2009).

By measuring users' biomechanical load such as their postures related to sitting and standing workstations, we found how users responded to the removal of the task chair and its back support by shifting their center of mass closer to the desk while standing. We also showed how these user-selected set ups for sitting and standing computer workstations induced different posture and muscle activity, both in terms of magnitudes and dynamic ranges. The results indicate that the standing workstation could be beneficial to users to work with a more neutral shoulder posture with smaller shoulder muscle load. However, user's perceived discomfort would increase with time, specifically related to low back discomfort. Therefore, we believe that the workstation intervention for long-hour seated computer work should not be only shifting to a standing computer workstation, but rather to an adjustable sit-stand workstation. The flexibility to alternate between a sitting and a standing computer workstation helps users receive shoulder health benefits through standing and avoid low back pain development through sitting (Gallagher et al, 2014; Pronk, 2011; Roelen et al. 2008; Tissot, Messing, and Stock 2009).

The study results need to be interpreted within its limitations. As the relationship between MSD risks and the exposure to sustained muscle activation and non-neutral postures remain unknown, the differences observed between the two workstations may have limited clinical significance. Nonetheless, the results were observed over only 45 minutes each trial, suggesting that further increases could occur over an 8-hour work day, which over time could represent a non-negligible accumulation of biomechanical loads during long terms of prolonged computer work (Hermans et al, 1998). Hence, the increases in non-neutral posture and muscle activation over time may still pose a risk for developing MSDs (Cooper and Straker 1998; Aaras et al. 1997; Kleine et al. 1999). The 45 minute sessions also led to conservative self-reported overall discomfort results, compared to a real life 8-hour workday. Additionally, the low back discomfort associated with standing work might potentially be mitigated by the intermittent sitting work as such an effect was reported previously (Gallagher et al, 2014). Finally, this is a laboratory study with pre-selected workstation components and designed computing tasks. The real-life office computer workstation may consist of more components and different work tasks than what were included in the study, and the psychophysical stress associated with a job was also not included in the study, which may further increase what were observed in the study.

Conclusions

By comparing users' biomechanical loads associated with a sitting and a standing computer workstation, the study demonstrates that, even with similar components, the differences in user-selected workstation set ups induced significantly different shoulder and wrist postures, and their associated shoulder and forearm muscle effort. Specifically for sitting, users took full advantage of the task chair and adopted a "reclined sitting" posture while working to transmit their upper body weight to the floor. While for standing, users responded to the removal of task chair and provided back support by standing closer to the desk and supporting part of their body weight with forearms. Most importantly, users reported similar discomfort levels within the first 10 minutes working with both a sitting and standing workstation, while after 45 minutes, the discomfort level for standing almost tripled that for sitting with most users reported low back discomfort being the main factor. The study results provided valuable insights regarding users' spontaneous adjustments within workstation constraints and their associated biomechanical loads and potential health consequences. We believe the results of this study can contribute towards making recommendations for ergonomic guidelines to set up standing computer workstations; it can also help users adjust timing of sitting and standing while using a computer workstation.

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Chapter 3

Evaluating the effect of four different pointing device designs on upper extremity posture and muscle activity during mousing tasks

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Abstract

The goal of this study was to evaluate the effect of different types of computer pointing devices and placements on posture and muscle activity of the hand and arm. A repeated measures laboratory study with 12 adults (6 females, 6 males) was conducted. Participants completed two mouse-intensive tasks while using a conventional mouse, a trackball, a stand-alone touchpad, and a roller-mouse. A motion analysis system and an electromyography system monitored right upper extremity postures and muscle activity, respectively. The roller-mouse condition was associated with a more neutral hand posture (lower inter-fingertip spread and greater finger flexion) along with significantly lower forearm extensor muscle activity. The touchpad and roller-mouse, which were centrally located, were associated with significantly more neutral shoulder postures, reduced ulnar deviation, and lower forearm extensor muscle activities. Users reported the most difficulty using the trackball and touchpad. Roller-mouse was not more difficult to use than any other devices. These results show that both device design and location elicit significantly different postures and forearm muscle activities during use, especially for the hand posture metrics.

Key Words: Pointing Device, Computer tasks, Musculoskeletal Disorders

Introduction

As the time spent using computers continues to increase both at home and in the workplace, the incidence of musculoskeletal disorder (MSD) associated with using computers has also increased (Cook, 2000). In particular, computer use has been found to be associated with MSDs in hand and arm than neck and shoulders, with stronger evidence suggesting hours of mouse activity being more of the culprit compared to keyboarding (Gerr, 2004, IJmker, 2007). Prolonged mouse use is associated with ergonomic risk factors including non-neutral postures and sustained muscle activity, specifically related to extreme ulnar deviation, wrist extension and forearm pronation (Burgess-Limerick, 1999, Jensen, 1998, Karlqvist, 1998, Sjøgaard, 1998). Accordingly, the specific design and placement of pointing devices has been evaluated to determine the effects on upper limb posture and muscle activity (Burgess-Limerick, 1999, Dennerlein, 2006, Jensen, 1998).

To date, most studies have investigated mostly wrist and shoulder postures along with forearm and shoulder muscle electromyography with only a few investigating hand postures. For example, several studies have shown that placement of the mouse closer to the center line of the operator reduces awkward shoulder and wrist postures as well as reducing muscle activity of both the forearm and the shoulder (Sommerich, 2002, Dennerlein, 2006, Kumar, 2008, Harvey, 1997). Several studies have shown that the design of the pointing device has little effect on neck and shoulder posture and muscle activity; however, they do have an effect on forearm muscle activity (Lee, 2005, Lee, 2008). The few studies that have investigated hand postures have only explored the button design and placement (Lee, 2007) or the size of notebook mice (Oude Hengel et al., 2008). Very little has been done to explore the effects of different pointing devices on hand or finger posture to provide a better link between the design of the device and effects on forearm muscle activity.

Therefore, this study aims to investigate the consequences of using different computer pointing devices during typical computer tasks. We evaluated four distinct device designs (a conventional mouse and three alternative pointing devices: a trackball mouse, a touchpad, and a roller-mouse), placed on the work surface according to their standard practices. We wanted to the consequences of different pointing devices on shoulder, wrist and hand posture, forearm muscle activity, and user perception during typical computer tasks. We hypothesize that exposure to non-neutral shoulder, wrist and finger postures, along with sustained forearm muscle load will differ across different pointing devices.

Methods

Twelve right-handed adult participants (6 females, 6 males) with no history of neck or upper extremity musculoskeletal injuries volunteered and provided written informed consent for this repeated measure laboratory study. The mean anthropometric measures for the participants were typical of the average United States population (Table 3.1). Harvard T. H. Chan School of Public Health Office of Regulatory Affairs and Research Compliance approved all protocols and informed consent forms. All participants completed the full study protocol using all four computer pointing devices to complete the two designed computer tasks while having their posture and muscle activity recorded real time continuously. The median value of user's posture and muscle effort data were compared across devices and tasks.

rticipant

	Males ($N = 6$)	Females ($N = 6$)	All
Age (yrs)	30.5 (8.5)	24.7 (1.5)	27.6 (6.6)
Height (cm)	173.2 (6.6)	166.7 (1.3)	169.9 (5.7)
Weight (kg)	68.8 (11.3)	60.0 (4.1)	64.4 (9.4)
Hand length (cm)	18.1 (0.6)	17.5 (0.9)	17.8 (0.8)
Hand breadth (cm)	9.1 (0.49)	8.5 (0.6)	8.8 (0.6)
Thumb CMC to tip (cm)	6.3 (0.6)	6.3 (0.4)	6.3 (0.5)

Pointing Device Conditions and Experiment Protocol

Each participant completed a series of standardized mousing tasks four times, each with a different pointing device: a generic mouse (Lenovo 06P4069 Black 3-Button Wired Optical Mouse), a trackball (Logictech TrackMan Marble), a standalone touchpad device (ADESSO Smart Cat 4-Button

Touchpad) , and a roller-style device (Contour Roller-Mouse Free 2). All devices were set to the same pointer speed at 6 of the 11- point scale in Microsoft Windows XP® with the acceleration function disabled. The setting requires a 100mm lateral mouse movement (or a 100mm-equivalent of trackball rotation along one axis) to move the cursor across a 520mm wide screen based on a 1600x1200 setting on a 24" computer screen. During the experiment, the mouse and the trackball were placed to the right side of the keyboard; whereas, the touchpad and the roller-mouse were placed between the participant and the keyboard, at the center of the table which are the conventional placement of these devices (Figure 3.1). For all conditions, the participants sat at the same workstation, which consisted of a chair with arm rests, a monitor, and a generic keyboard with no number keypad. The height of the chair was adjusted such that the participant's feet could remain on the floor and the thighs would be parallel with the floor throughout the experiment. The height of the desk was set such that the j-h key of the keyboard was at resting elbow height. The location of the monitor and the keyboard were kept constant for all conditions.

For each device, participants completed two distinctive computer tasks: first three minutes of playing Solitaire and then five minutes of web browsing requiring reading and answering specific reading comprehension questions. Playing solitaire, which requires point-and-click and point-and-drag tasks in various areas of the computer screen, provided an opportunity for participants to familiarize themselves with cursor operations using different devices. The customized web browsing tasks involved both cursor operations (cursor movement, point-and click and point-and-click) along with intermittent keyboard operations (typing) to simulate office work that often requires interactions with both the keyboard and the designated pointing device. The web browsing task required approximately 90% mousing and 10% typing operation. The order of different pointing device conditions presented to participants was randomized, with a two-minute break provided between tasks.

Figure 3.1: The general arrangement of the keyboard and pointing device for the four devices tested (A) Standard Mouse (B) Track Ball, (C) Touch Pad, and (D) Rollermouse. Instructions to participants allowed them to make adjustments to the specific location of the mouse and trackball, but to keep the general arrangement of the device relative to the keyboard as outlined in these photos. Instructions for the touch pad and rollermouse asked the participants not to make any adjustments of the relative location of the device relative to the keyboard.

Dependent Variables: Posture

An optical three-dimensional motion analysis system (Optotrak Certus, Northern Digital, Ontario, Canada) recorded hand and upper limb posture. Infrared light-emitting diodes (IRLEDs) were mounted on each fingertip and proximal interphalangeal joint (PIP) of the participant's right hand. A rigid body cluster consisting of three IRLEDs attached to a metal structure was attached to the back (dorsal) side of the hand over the 3rd metacarpal bone between the wrist and knuckle. Three additional rigid bodies were attached to the forearm, upper arm, and chest. Locations of bony landmarks (right and left acromion, sternal notch, lateral and medial epicondyle of the right elbow, radial and ulnar styloid of the right wrist, metacarpophalangeal joints for digits II-IV of the right hand) were palpated, digitized and tracked according to their corresponding body segment IRLED cluster. Location data for each IRLED and digitized point were subsequently filtered through a low-pass, fourth-order Butterworth filter with a 10 Hz cutoff frequency and used to define local coordinate systems for each segment (Asundi et al., 2010, Asundi et al., 2012, Winter, 2005).

Using the anatomical position and the vertical as reference, joint angles were defined by the rotation matrices describing the orientation of the distal segment relative to the proximal segment. Specifically, from the local coordinate systems, rotation matrices were calculated to obtain the upper arm orientation relative to the torso, the forearm relative to the upper arm, and the hand/wrist orientation relative to the forearm. With these local rotation matrices, Euler angles for all body segments of interest were calculated to describe flexion, extension, abduction, adduction, and rotation (internal or external) of the right shoulder, elbow, and wrist (Asundi et al., 2010, Asundi et al., 2012, Winter, 2005).

Hand posture was quantified using two metrics: inter-fingertip spread and finger flexion. Inter-fingertip spread was defined as the distance between the adjacent finger tips (thumb to index, index to middle, middle to ring, and ring to little), calculated using the distance between the fingertip IR-LED markers (Figure 2). Finger flexion for index, middle, ring, and little fingers was defined as the metacarpophalangeal (MCP) joints flexion angle, calculated using the IRLED on the PIP joint, each virtual MCP marker, and the rigid body on the back of the hand.

Dependent Variables: Muscle Activity

Surface electromyography (EMG) electrodes (DE-2.1 Single Differential Electrode; Delsys, Boston, Massachusetts, USA) measured muscle activity for the right middle trapezius, three right shoulder muscles (anterior, medial and posterior deltoids), and four muscles of the right forearm (extensor digitorum(ED), extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), and Extensor pollicis brevis (EPB)). The electrodes were placed in standard locations as defined by Perotto (Perotto, 1994). Electrode placement on the muscles was achieved through palpation and validated through EMG signal response to corresponding muscle contraction exercises. After amplification, EMG signals were recorded at a frequency of 1000 Hz, rectified, and smoothed using a 3 Hz low pass filter. In order to normalize the signals for interested muscles, three 3-second isometric maximum voluntary contractions (MVC) were collected for each muscle with corresponding exercises. Participants were coached to gradually ramp up to reach an MVC by the experimenter while the experimenter resisted participants' force exertions using up to their entire bodyweight. Participants were given 2 minutes between the same muscle contraction and the maximum signal obtained was used as the MVC reference. Based on these references, normalization of EMG was calculated by percent MVC of each muscle. The median muscle activity levels in percent MVC were used to compare across participants.

Dependent Variables: User Perception

All participants responded to two survey questions about overall upper extremity discomfort and task difficulty after completing the two computer tasks for each device. The responses were marked on a 10-cm visual analogue scale (VAS) with 0 being the lowest level of discomfort/difficulty and 10 being the highest.

Data and Statistical Analysis

For all dependent variables, including posture (in angles), muscle activity (in percentage MVC), and user perception (VAS scale from 0 to 10), marginal means and standard errors were calculated and used as the outcome measure for each task on each device. Variation for each outcome measure across the four device conditions and two software tasks was tested using repeated measures analysis of variance (RM-ANOVA), with participant included as a random effect. Interaction between Device and Task was included in the model. Significance criteria (alpha value) was set at 0.05. When a significant effect was found, a post-hoc analysis with Tukey's honest significance test was conducted across the four input devices and two tasks. Statistical analysis was performed using JMP Pro 10 (SAS) linear mixed model module software.

Results

Posture

Hand postural metrics differed significantly between devices for the index, middle and ring fingers only (Table 3.2). The inter-finger distances between index and middle finger, and middle and ring finger differed significantly across pointing devices with the smallest distances observed with the roller-mouse. The roller-mouse was also associated with significantly greater middle and ring finger flexion compared to the other devices tested, along with similar value as the touchpad for the lowest level for index finger flexion. Task had a small but significant effect on index-middle and middle-ring fingertip distance: distances were greater when playing Solitaire than when web surfing. No interaction terms were significant.

All upper limb postures differed significantly across pointing devices (Table 3.3). Shoulder abduction and shoulder flexion were significantly greater for the laterally located mouse and trackball; whereas internal rotation and forearm rotation were significantly greater for the centrally located touchpad and roller-mouse. Ulnar deviation was greatest for the trackball and least for the touchpad. Wrist extension was significantly lower for the mouse than for the other devices. The main effect of task and the interaction term between task and device was not significant for any upper limb postural outcome.

Table 3.2: Hand Posture: Across participant marginal means (and standard errors) for RMANOVA Device, Task, and their Interaction.

	Device					Task			Condition x task
	p-Value[a,b]	Mouse	Track ball	Touchpad	Roller mouse	p-Value	Solitaire	Web surfing	p-Value
Inter-fingertip distance (mm)									
Thumb to Index	0.06	54 (4)	62 (4)	55 (4)	58 (4)	0.40	56 (4)	58 (4)	0.66
Index to Middle	**<0.0001**	37 (2)^{A}	30 (2)^{B}	29 (2)^{B}	21 (2)^{C}	**0.03**	31 (2)	28 (2)	0.56
Middle to Ring	**<0.0001**	28 (3)^{A}	28 (3)^{A}	24 (3)^{B}	23 (3)^{B}	**0.01**	27 (3)	25 (3)	0.21
Ring to Little	0.16	40 (4)	42 (4)	45 (4)	41 (4)	0.25	44 (4)	42 (4)	0.24
MCP joint flexion angle (°)[c]									
Index	**<0.0001**	27 (3)^{B}	23 (3)^{B}	40 (3)^{A}	40 (3)^{A}	0.09	31 (2)	34 (2)	0.91
Middle	**<0.0001**	22 (2)^{C}	22 (2)^{C}	39 (2)^{B}	44 (2)^{A}	**0.03**	30 (2)	33 (2)	0.58
Ring	**<0.0001**	21 (3)^{C}	17 (3)^{C}	28 (3)^{B}	34 (3)^{A}	0.16	24 (3)	26 (3)	0.81
Little	0.18	25 (4)	22 (4)	26 (4)	29 (4)	0.49	25 (4)	26 (4)	0.80

[a] Repeated Measures Multivariate ANOVA with participant as a random variable, fixed effects Device (4 levels), Task (2 levels) and their interaction. Bold values indicate a significant effect ($p < 0.05$).
[b] For significant main effects, Tukey's Post-Hoc groupings are ranked such that A > B > C > D. Values with the same superscript letters indicate no significant difference.
[c] Angle of flexion for metacarpophalangeal (MCP) joints of fingers II-V where 0° indicates the MCP-PIP vector is parallel to the hand plane.

Table 3.3: Upper Limb Posture: Across participant marginal means (and standard errors) for RMANOVA Device, Task, and their Interaction. All angles were calculated in relation to the reference posture.

Angle (°)	Device					Tasks			Condition × task interaction
	P-value[a,b]	Mouse	Track ball mouse	Touchpad	Roller mouse	P-value	Solitaire	Web surfing	P-value
Shoulder abduction	**<0.0001**	14 (2)^{A}	13 (2)^{A}	9 (2)^{B}	7 (2)^{B}	0.91	11 (2)	11 (2)	0.64
Shoulder flexion	**<0.0001**	25 (6)^{A}	23 (6)^{A}	9 (6)^{B}	12 (6)^{B}	0.06	16 (6)	18 (6)	0.63
Shoulder internal rotation	**<0.0001**	0 (2)^{C}	3 (2)^{C}	29 (2)^{A}	25 (2)^{B}	0.25	14 (2)	15 (2)	0.19
Elbow flexion	**0.0160**	12 (3)^{A}	10 (3)^{A}	7 (3)^{A,B}	0 (3)^{B}	0.94	7 (2)	7 (2)	0.91
Forearm supination	**0.1153**	21 (5)	7 (5)	14 (5)	19 (5)	0.53	16 (3)	14 (3)	0.56
Wrist adduction	**<0.0001**	9 (2)^{B}	12 (2)^{A}	1 (2)^{D}	6 (2)^{C}	0.33	7 (2)	7 (2)	0.30
Wrist extension	**0.0340**	16 (3)^{B}	19 (3)^{A,B}	21 (3)^{A}	19 (3)^{A,B}	0.23	18 (3)	19 (3)	0.37

[a] Repeated Measures Multivariate ANOVA with participant as a random variable, fixed effects Device (4 levels), Task (2 levels) and their interaction. Bold values indicate a significant effect ($p < 0.05$).
[b] For significant main effects, Tukey's Post-Hoc groupings are ranked such that A > B > C > D. Values with the same superscript letters indicate no significant difference.

Muscle Activity

Muscle activity varied significantly only for the forearm muscles (Extensor Digitorum, Extensor Carpi Ulnaris and Extensor Carpi Radialis) across devices (Table 3.4). Significantly lower Extensor Carpi Radialis muscle activity was observed for the roller-mouse compared to all other devices. The trackball was associated with the greatest forearm muscle activity, and had median values greater than 10% MVC for the Extensor Digitorum and Extensor Carpi Ulnaris. The main effect of Task was significant only for the trapezius: Solitaire had slightly lower muscle activity than web surfing. The interaction between Task and Device was not significant for any muscle activity outcome.

User Perception

Participants reported significantly less difficulty using the traditional mouse than using the trackball and touchpad; the roller-mouse was reported to be no different from the three other devices (Table 5). Mouse and roller-mouse had the lowest discomfort level reported, though difference was not significant with a p-value of 0.054.

Table 3.4: Muscle Activity: Across participant marginal means (and standard errors) for RMANOVA Device, Task, and their Interaction.

Median EMG activity (% MVC[c])	Device					Tasks			Condition × task interaction
	P-value[a,b]	Mouse	Track ball mouse	Touchpad	Roller mouse	*P*-value	Solitaire	Web surfing	*P*-value
Middle Trapizius	0.28	2.8 (0.4)	2.4 (0.4)	2.4 (0.4)	2.3 (0.4)	**0.0001**	2.1 (0.3)	2.9 (0.3)	0.89
Anterior Deltoid	0.47	0.8 (0.2)	0.6 (0.2)	0.8 (0.2)	0.8 (0.2)	0.58	0.8 (0.1)	0.7 (0.1)	0.31
Middle Deltoid	0.10	1.4 (0.3)	1.2 (0.3)	1.6 (0.3)	1.2 (0.3)	0.57	1.4 (0.3)	1.3 (0.3)	0.79
Posterior Deltoid	0.40	1.1 (0.2)	1.1 (0.2)	1.2 (0.2)	1.1 (0.2)	0.90	1.1 (0.2)	1.1 (0.2)	0.39
Extensor Digitorum	**<0.0001**	8.7 (0.7)[B]	10.2 (0.7)[A]	7.9 (0.7)[B,C]	6.9 (0.7)[C]	0.83	8.4 (0.7)	8.4 (0.7)	0.99
Extensor Carpi Ulnaris	**<0.001**	8.9 (1.9)[A,B]	10.2 (1.9)[A]	7.8 (1.9)[B]	8.4 (1.9)[B]	0.89	8.8 (1.8)	8.8 (1.8)	0.58
Extensor Carpi Radialis	**<0.0001**	7.6 (1.0)[A]	8.3 (1.0)[A]	7.8 (1.0)[A]	6.6 (1.0)[B]	0.90	7.6 (1.0)	7.6 (1.0)	0.73
Extensor Pollicis Brevis	0.11	5.2 (1.0)	5.1 (1.0)	5.8 (1.0)	4.8 (1.0)	0.14	5.5 (1.0)	5.0 (1.0)	0.73

[a] Repeated Measures Multivariate ANOVA with participant as a random variable, fixed effects Device (4 levels), Task (2 levels) and their interaction. Bold values indicate a significant effect ($p < 0.05$).
[b] For significant main effects, Tukey's Post-Hoc groupings are ranked such that A > B > C > D. Values with the same superscript letters indicate no significant difference.
[c] Maximum Voluntary Contraction.

Table 3.5: User Perception: Across participant marginal means (and standard errors) for RMANOVA from participant survey under each condition.

User's feedback	Device				
	P-value[a,b]	Mouse	Track ball mouse	Touchpad	Roller mouse
Difficulty	**<0.001**	0.6 (0.4)[B]	2.6 (0.4)[A]	2.6 (0.4)[A]	1.5 (0.4)[A,B]
Discomfort	0.05	0.9 (0.5)	2.1 (0.5)	1.2 (0.5)	0.8 (0.5)

[a] One-way repeated measures ANOVA with participant as a random variable. Values in bold indicate a significant effect ($p < 0.05$).
[b] For significant main effects, Tukey's Post-Hoc groupings are ranked such that group A > B > C > D. Values with the same superscript letters indicate no significant difference.

Discussion

The goal of this study was to determine the effects of different pointing devices on hand posture and forearm muscle activity. Consistent with our hypothesis, the results indicate that the degree of exposure to biomechanical risk factors such as non-neutral hand posture and increased forearm muscle load differ across pointing devices. The rollermouse condition had the smallest finger spread, greatest finger flexion and lowest forearm extensor muscle activity (Extensor Digitorum, Extensor Carpi Ulnaris, Extensor Carpi Radialis). Both touchpad and rollermouse conditions were associated with a more neutral shoulder posture and smaller wrist abduction. The results of the present study suggest that specific alternative pointing devices produced more neutral postures of the fingers, wrist and shoulder.

The novel finding of our study is that different pointing devices induce significantly different finger posture and forearm muscle activity due to the design and affordance of each device. In the present study, we defined a neutral hand posture according to the physical therapy definition of a relaxed resting position. Such a posture has the fingers gently curved and less spread apart; where fingers that are closer to fully straightened out (less flexed) are considered less neutral (Warren, n.d.). During the experiment, the size and shape of the mouse and the trackball, allow users to rest their palm while holding the device. However, mouse users lift their index and/or middle finger(s) to click or scroll and trackball users scroll the tracking ball with one or two specific finger(s) while holding the device with the rest of the fingers. These constraints increased inter-finger spread, lowered finger flexion, and increased forearm muscle activity for both the mouse and the trackball conditions. Unlike a mouse and a trackball, the design of the touchpad eliminated the need to hold the device and therefore induced greater finger flexion and smaller finger spread. By specifically comparing to a mouse, we found that the touchpad allowed user to keep their index, middle, and ring finger closer together, which resulted in significantly smaller index to middle (-7mm mean difference with 95%CI of [-12, -3]mm) and middle to ring (-4mm mean difference with 95%CI of [-7, -1]mm) finger distances (Table 2b). Additionally, touchpad use also resulted in lower forearm muscle activity, which may be explained Lee et al’s work (Lee, 2007) that showed lower forearm muscle activity for pointing device use could be explained by the lower frequency and/or duration of "lifted finger" observed.

The finding that the roller mouse had more neutral posture and lower forearm muscle load suggests the design and affordance of a pointing device significantly affect the interactions between the hand and the device. Similar to a touchpad, the design of the rollermouse allowed users to control cursor movement and clicks using almost any part of their hand without needing to hold the device or click using one specific finger. In fact, eleven out of the twelve users were observed to scroll the roller-bar with all four fingers close together while tapping on the roller-bar without much finger lifting. Compared to mouse (Table 2b), the inter-finger distance between index and middle finger for the rollermouse was significantly lower with a mean difference of -15mm and a confidence interval of [-11, -20] mm. Additionally, rollermouse allowed user to flex 13° [8°, 18°] more for the index finger, 22° [17°, 27°] more for the middle finger, and 13° [8°, 19°] more for the ring finger. While trackball was found to have even greater inter-finger spreads and smaller finger flexion, the rollermouse allowed for a more neutral hand posture with greater finger flexion and smaller finger spread compared to both a mouse and a trackball. Furthermore, a more neutral hand posture with smaller index-middle finger spread and greater middle and ring finger flexion was associated with the rollermouse compared to a touchpad (Table 3a). This may be explained by the design of the rollermouse which allows multiple fingers to operate the device. The touchpad requires users to operate with a single finger while keeping other fingers from contacting the track pad to avoid unintended cursor operation. This causes the greater index-middle finger spread and less flexion (greater extension) of the middle and ring fingers which we observed.

The shoulder and wrist postures appeared to be associated with the placement of the device. Specifically, devices placed laterally (mouse and trackball) induced greater shoulder abduction, shoulder flexion and rotation; whereas, devices placed near the centerline and close to the body (touchpad and rollermouse) were associated with a more neutral posture. Specifically comparing the touchpad and the rollermouse to the generic mouse, we found that touchpad and rollermouse had significantly smaller shoulder abduction (-5° [-8°, -2°] and -7°[-10°,-4°], respectively) and shoulder flexion (-15° [-20°,-11°] and -13°[-17°,-9°], respectively), but greater shoulder internal rotation (+30°[+26°,+34°] and +25°[+21°,+29°], respectively).This is consistent with previous work done by Dennerlein et al in 2006 and Sommerich et al in 2002, which reported greater shoulder abduction, flexion, external rotation, and ulnar deviation values measured for a mouse located on the right side of the keyboard compared to the center (Dennerlein, 2006, Sommerich, 2002). The effect of pointing device placement on posture and muscle activity of the upper extremity was reduced in the study since a keyboard without a number pad was used instead of a full-size keyboard. Many studies have shown a reduction in shoulder flexion, abduction, external rotation and reduced trapezius and deltoid muscle activities when the number keypad is removed(Sommerich, 2002, Karlqvist, 1998). The present study did not find significant difference for MT and MD muscle activity across pointing devices, which may be due to participants supporting their forearms on the desk surface and altering the relationship between sustained postures and muscle load (Delisle, 2006, Kotani, 2007).

The conclusions of this study need to be considered within their limitations. First, this is a laboratory study and is based on an ideal placement for each pointing device. Hence, the generalizability of our results may be limited as the data were collected during a designed set of tasks with an ideal work station setup. The added features and settings for the pointing devices may differ from those at a work place, and the experiment did not incorporate psychological pressure of a real world paying job that can also affect the biomechanics of the participants. Secondly, since the relationship between MSD risks and the exposures to awkward posture and sustained muscle activity remains unknown, the muscle activity differences across pointing device operations observed in our study may have limited clinical relevance. Thus, the direct association and the dose-response effect between a 2%MVC difference observed in our study and the MSD risks remains unknown. Nonetheless, the effect of these small differences in posture and muscle activity may have a greater impact if the duration and frequency of exposure accumulate during a work day. There are also anecdotes in published reports that show alternative pointing devices do help people who have existing upper extremity pain (Dardashti, 2003)

All participants were familiar with the use of the mouse, trackball and touchpad, but had no previous experience working with a rollermouse. However, it was still deemed easy to use compared to the other devices tested. As both a rollermouse and a touchpad can be operated using both hands, potential future studies could focus on forearm and hand posture monitoring of both hands. This study was not a full factorial design in terms of device placement as the experiment focused on devices being used for their standard practice at a work place. Future studies may investigate placing all pointing devices at the same location relative to the user to reduce the effect of device placement on users' shoulder and wrist postures. A future comparison between pointing devices included in the study with tablet computers with all devices being centrally placed may be informative as tablet computers have become more popular in office and home work settings.

Conclusions

Overall, the study demonstrates that different degrees of exposures to non-neutral postures and sustained muscle activity are dependent on the design and the placement of the pointing devices. The findings also suggest that hand postures should be monitored when evaluating pointing devices as the affordance of pointing devices can cause non-neutral finger and hand postures that induce significantly different forearm muscle activities.

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Chapter 4

Screen location of swipe gesture affects thumb biomechanics and performance during two-handed use of tablet computers

Abstract

Sixteen adult (8 female, 8 male) participants completed various thumb swipe actions using their right thumb while holding the device with two hands. All participants completed 320 tablet swiping actions across four designated swiping locations, with various tablet size (8" and 10"), tablet orientations (Portrait and landscape), swipe orientation (vertical and horizontal), and swipe directions (medial and radial). Posture of the thumb and wrist and forearm muscle activity were measured using 3-D motion analysis and surface electromyography. User's average completion time for 5 repetitive swipes was recorded as the performance measure. User perception associated with specific swipe location and orientation was assessed using questionnaire. Overall, swipe location closest to the palm allowed users to swipe with a more neutral thumb and wrist posture and requires less forearm muscle effort. As swipe location gets further either towards the upper edge or the center of the tablet, greater thumb extension and abduction along with greater wrist extension and adduction is require to reach the target. Forearm muscle activities associated also increased significantly. The study results demonstrates that under certain user configurations, the location of swipe gestures on the screen matters and through some hardware and software designs the interface can be improved to induce more neutral thumb and wrist posture, lower forearm muscle load, while shorten task completion time.

Introduction

Moving away from stationary computer workstations, computer users are now migrating to portable units such as the tablet computer because of their mobility and functional versatility. In fact, the term "phablet" is becoming more popular by the day as it represents a class of a mobile device designed to combine or straddle the form of a smartphone and a tablet. While these mobile devices are designed to be multi-functional with an often intuitive software interface, their designs may challenge users' biomechanical capabilities and could increase users' risks of developing musculoskeletal disorder (MSD) associated with overuse.

Several studies have explored how the design and configuration of these devices examine biomechanical factors associated with the development of upper extremity MSDs as well as performance related issues of user experiences with these devices. There is evidence that certain display and hand holding configurations of tablet use can lead to increased neck and head flexion, as well as increased wrist flexion and extension (Young 2012; Trudeau 2013). Pereira et al found that during one hand tablet use, smaller to medium-size tablets with a ledge or handle on the back associate with greater overall usability (Pereira et al, 2013).

Previous research has shown that both tablet orientation (portrait/landscape) and its soft keyboard layout can significantly affect users' thumb posture, perceived-comfort and motor performance, while performing a tapping task during two-handed use of tablet computers (Trudeau et al, 2013). Next to the tap, the most common gesture is the swipe where, in the case of the two-handed user configuration, the thumb touches the surface and moves in one direction to activate a specific software task. Few have explored the touch gestures and their configuration in terms of thumb biomechanics and motor performance.

In the current study, we sought out to determine the effect of tablet form factor (size, orientation, configuration) and swiping gesture design (orientation and direction) on thumb swiping motor performance, thumb posture, forearm muscle activity and self-reported discomfort across configurations for a two-handed grip on a tablet device. We expect that swiping performance, self-reported factors and forearm muscle activity would differ across the gesture design and form factor. These differences could be due to different thumb and wrist postures required to perform swiping tasks, requiring thumb reaching while holding the device during two-handed grip configurations. Specifically, we hypothesize that during swiping the bottom right location of the tablet would require less reach than the top left location of the tablet and that we can measure this as 1) lower forearm muscle effort and lower self-reported discomfort; 2) shorter swipe completion time compared to the top left location.

Method

Study population

Sixteen healthy right-handed participants (8 males and 8 females, aged from 21 to 40 years old) with no history of MSDs were recruited for the study. Harvard T.H. Chan School of Public Health Office and regulatory Affairs and Research Compliance and Northeastern University office and committee on Human Subject Research Protection approved all protocols and informed written consent forms. The mean anthropometric measures for the participants were typical of the average United States population (Table 4.1). For the testing protocols, participants sat on a task chair without arm supports. All nearby light sources were indirect lighting and there was no glare on the tablet's screen. Participants were instructed to hold the tablet with two hands and interact with the tablet only with their thumbs without dropping the tablet. Participants were allowed to support their forearm on their thigh if needed.

Table 4.1: Anthropometric measures of means (standard deviations) across all participants

	Males (N=8)	Females (N=8)	All
Age (yrs)	25 (4)	24 (3)	24.5 (3)
Height (cm)	180 (8)	167 (7)	173.4 (10)
Weight (kg)	74 (20)	61 (6)	68 (14)
Hand Length (cm)	20 (0.8)	18 (1)	19 (1)
Hand breadth (cm)	8.8 (0.6)	7.4 (0.4)	8.1 (1)
Thumb length (cm)	10 (1)	9.7 (1)	10 (1)

Tablet Instrumentation and Experimental Tasks

Participants performed 64 thumb swiping gestures with the thumb of their right hand. The swipe gestures differed in swipe direction (normal vs. reverse), swipe orientation (horizontal vs. Vertical), tablet size (small vs large), tablet orientation (portrait vs. landscape) and swipe length (short vs long) each action was repeated five times (Table x).

The swipe gesture required the user to move a cursor along and within a lane created by two lines a specified distance apart (10 mm) for a specified distance (short 20 mm or long 60 mm). To complete the swipe gesture, participants had to touch the screen activating a target bar (10mm x 2mm) and then steer the bar (Allcot and Zhai, 1996) between two lines while keeping the thumb between the two lines. The gesture was completed when the thumb reached and passed the end of these lines without movement going outside the lane formed by these two lines. A custom native application was created to collect completion time data and provide visual guidance for users. The application was created for an Android platform.

The order of task presented was randomized and balanced across participants. The two tablet computers selected in the study were Samsung Galaxy III with a 10” display (Samsung Inc.) and a

Samsung Galaxy Note III with an 8” display (Samsung Inc.). The application presented each action/location to the participant in a balanced randomized fashion (Figure 4.1).

Dependent Variables: Posture

Participants’ hand and upper limb postures were calculated from data recorded using an optical three-dimensional motion analysis system (Optotrak Certus, Northern Digital, Ontario, Canada). Infrared light-emitting diodes (IRLEDs) were mounted on the tip, interphalangeal joint (IP), metacarpal (MCP) and carpometacarpal (CMC) joint of the participant’s right thumb. A rigid body cluster consisting of three IRLEDs was attached to a metal structure and attached to the back (dorsal) side of the right hand over the 3rd metacarpal bone between the wrist and MCP joint. A second rigid body was attached to the dorsal side of the right forearm approximately two inches proximal to the right wrist. Locations of bony landmarks (lateral and medial epicondyle, lateral and medial styloid, and metacarpophalangeal joints for digits II-IV of the right hand) were palpated, digitized and tracked corresponding to the hand rigid body. Location data for each IRLED and digitized point were subsequently filtered through a low-pass, fourth-order Butterworth filter with a 10 Hz cutoff frequency to define local coordinate systems of the thumb, hand and forearm. The IRLED placement used in this study builds on previous methods for measuring thumb-tablet interactions (Asundi et al., 2012; Trudeau, 2013; Winter, 2005).

The wrist and thumb joint angles were calculated using the Euler angles of the rotation matrices describing the orientation of the joint’s distal segment relative to the proximal segment (Winter, 2005). We presented joint angles relative to a reference posture in which forearm and hand were aligned along its longitudinal axis, and the thumb was extended and straightened to the lateral side of the index finger. The posture results were based on the assumption that the wrist has two degrees of freedom (abduction/adduction, flexion/extension), the thumb CMC joint has three degrees of freedom (abduction/adduction, flexion/ extension, pronation/supination), the thumb MCP joint has two degrees of freedom (abduction/adduction, flexion/extension), and the thumb IP joint has a single degree of freedom (flexion/extension). For study comparison, median joint angles and joint ranges of motion (90^{th} minus 10th percentile) were calculated as metrics to describe hand and thumb posture for each trial. (Trudeau, 2013; Dennerlein, 2006).

Dependent Variables: Muscle Activity

Surface electromyography (EMG) electrodes (DE-2.1 Single Differential Electrode; Delsys, Boston, Massachusetts, USA) measured 8 muscles groups of the right forearm including Extensor Digitorum (ED), Extensor Carpi Radialis (ECR), Extensor Carpi Ulnaris (ECU), Extensor Pollicis Brevis (EPB), Abductor Pollicis Longus (APL), Flexor Digitorum Superficialis (FDS), Flexor Carpi Radialis (FCR), and Flexor Carpi Ulnaris (FCU). The electrodes were placed in standard locations based on previous experience and as defined by Perotto (Lin, 2015; Perotto, 1994). Electrode placement on the muscles was achieved through palpation and validated through EMG signal response to corresponding muscle contraction exercises. The EMG sampling rate was 1000 Hz. Upon amplification, EMG signals were rectified, and smoothed using a 3 Hz low pass filter. Three 3-second isometric maximum voluntary contractions (MVC) were collected for each muscle with corresponding exercises to normalize the signals for interested muscles. Participants were coached to gradually ramp up to reach their maximal exertions while the experimenter resisted using up to their entire bodyweight. The highest value of the 3 exertions was designated as the 100% MVC. A minimum break of at least two minutes was taken between testing of each muscle group. Based on these references, normalization of EMG was calculated as percent MVC of each muscle. The 10^{th} percentile, median, and 90^{th} percentile muscle activity levels in percent MVC were used to compare across participants.

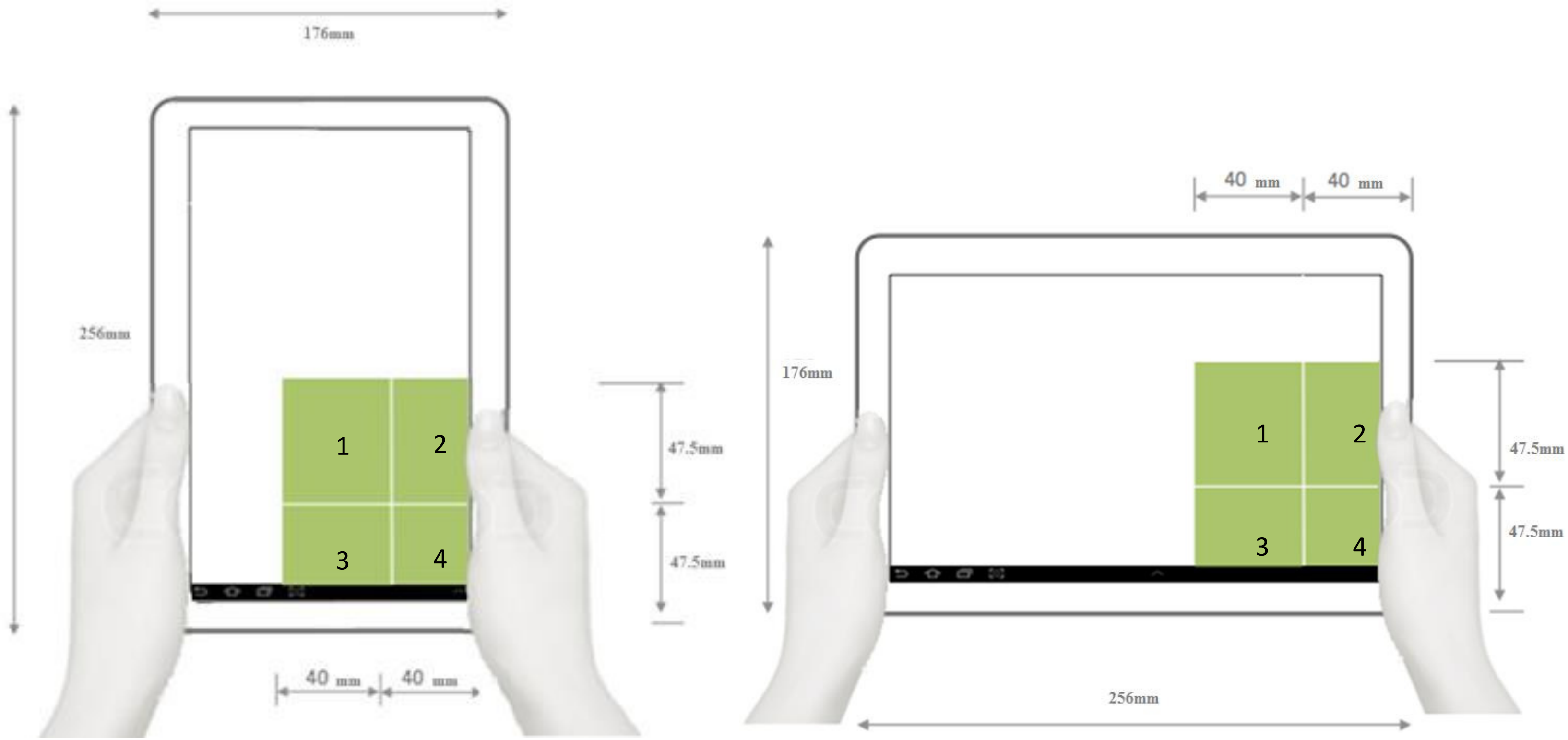

Figure 4.1a and 4.1b: The screen was partition into four location denoting the start and finish of each swipe gesture. Portrait and landscape swipe locations on the screen. The thumb swipe initial locations (Short slider target zone= 20 mm x 10mm or Long slider target zone=60 mm x 10 mm) were located in the center of each swipe location.

Table 4.2: Different gestures considered in the tablet study. The study protocol is consisted of four sets of the presented swiping actions randomized across two different tablet sizes (8” and 10”) and orientations (portrait and landscape).

#	Tasks	type	direction	Starting location	Finish Location
1	Slider_horiz	long	normal	1	2
2	Slider_horiz	long	reverse	2	1
3	Slider_horiz	long	normal	3	4
4	Slider_horiz	long	reverse	4	3
5	Slider_vert	long	normal	1	3
6	Slider_vert	long	reverse	3	1
7	Slider_vert	long	normal	2	4
8	Slider_vert	long	reverse	4	2
9	Slider_horiz	short	normal	1	1
10	Slider_horiz	short	reverse	1	1
11	Slider_horiz	short	normal	2	2
12	Slider_horiz	short	reverse	2	2
13	Slider_vert	short	normal	3	3
14	Slider_vert	short	reverse	3	3
15	Slider_vert	short	normal	4	4
16	Slider_vert	short	reverse	4	4

Dependent Variables: Self-reported discomfort

All participants responded to eight survey questions about overall hand and wrist discomfort after completing each condition with each tablet. The responses were marked on a 10-cm visual analogue scale (VAS) with 0 cm being the lowest level of perceived-discomfort and 10 cm being the highest.

Data and Statistical Analysis

A repeated measures ANOVA (RMANOVA) evaluated the effect of each independent variable. For all dependent variables, including posture (in angles), muscle activity (in percentage MVC), and user perception (VAS scale from 0 to 10), marginal means and standard errors were calculated and used as the outcome measure. For each ANOVA model, we included participant as a random effect and all five independent variables (tablet size, tablet orientation, swipe direction, swipe location, swipe orientation) as fixed effects, as well as all possible two-way interaction terms. None of the three-way and higher interaction terms were significant. Significance criteria (alpha value) was set at 0.05. When a significant effect was found, either a post-hoc analysis with Tukey's honest significance test or a student's t-test was conducted across the variable. Statistical analysis was performed using JMP Pro 11 (SAS) linear mixed model module software.

Results

Posture

Thumb postures differed significantly across swipe locations (Table 4.3a). Specifically, the top left swipe location associated with smaller IP flexion (6^o), MCP flexion (12^o), CMC pronation (0^o), but greater MCP and CMC abduction (16^o and 7^o, respectively). The bottom left location was associated with the greatest CMC abduction (10^o). The bottom right location associated with greater IP flexion (40^o), MCP flexion (20^o), CMC pronation (3^o), but smaller MCP and CMC abduction (10^o and 0^o, respectively). Horizontal swipe gesture associated with greater MCP abduction (15^o) and flexion (18^o), and CMC abduction (4^o), compared to vertical swipe gesture. Additionally, thumb swipes in the top left and the bottom left swipe zones required greater ranges of thumb movement compared to the top right and the bottom right swipe zones (Table 4.3b).

For the wrist, the top left swipe location had the greatest wrist abduction (18^o) and extension (14^o) compared to the other three locations, while the bottom right location had the smallest. 10" tablet associated with greater wrist extension (14^o) compared to 8" (12^o). Landscape tablet orientation associated with greater wrist abduction (16^o) compared to portrait orientation (14^o). Similar to the thumb, the required wrist range of movement was also greater in the top left and bottom left swipe zones compared to the top right and bottom right swipe zones.

Table 4.3a: Thumb and wrist posture: Across participant marginal means and standard errors for ANOVA results

	Wrist		CMC			MCP		IP
	Extension(°)	Adduction(°)	Extension(°)	Abduction(°)	Pronation(°)	Flexion(°)	Abduction(°)	Flexion (°)
Tablet Size								
P-value	**0.01**	0.09	0.80	0.32	0.78	0.44	0.65	0.23
8”	**12(2)** ^{B}	15 (2)	6 (3)	3 (2)	1 (2)	17 (2)	14 (2)	31 (4)
10”	**14 (2)** ^{A}	16 (2)	6 (3)	4 (2)	1 (2)	17 (2)	14 (2)	29 (4)
Tablet Orientation								
P-value	0.55	**0.03**	0.91	0.22	0.89	0.18	0.58	0.08
Portrait	12(2)	**14 (2)** ^{B}	6 (3)	3 (2)	2 (2)	18 (2)	15 (2)	30 (4)
Landscape	12(2)	**16 (2)** ^{A}	6 (3)	4 (2)	1 (2)	17 (2)	14 (2)	29 (4)
Swipe Location								
P-value	**<0.0001**	**<0.0001**	0.28	**<0.0001**	**0.03**	**<0.0001**	**<0.0001**	**<0.0001**
1 (Top left)	**14 (2)** ^{A}	**18 (2)** ^{A}	7 (3)	**7 (2)** ^{B}	**0 (2)** ^{B}	**12 (2)** ^{C}	**16 (2)** ^{A}	**6 (4)** ^{D}
2 (Top right)	**11 (2)** ^{B}	**16 (2)** ^{B}	7 (3)	**0 (2)** ^{C}	**1 (2)** ^{B}	**14 (2)** ^{BC}	**11 (2)** ^{B}	**25 (4)** ^{B}
3 (Bot left)	**13 (2)** ^{A}	**15 (2)** ^{B}	6 (3)	**10 (2)** ^{A}	**1 (2)** ^{B}	**16 (2)** ^{B}	**17 (2)** ^{A}	**17 (4)** ^{C}
4 (Bot right)	**11 (2)** ^{B}	**13 (2)** ^{C}	6 (3)	**0 (2)** ^{C}	**3 (2)** ^{A}	**20 (2)** ^{A}	**10 (2)** ^{B}	**40 (4)** ^{A}
Swipe Orientation								
P-value	0.15	0.12	0.77	**<0.0001**	0.64	**<0.0001**	**<0.0001**	0.07
Horizontal	12(2)	16 (2)	6 (3)	**4 (2)** ^{A}	1 (2)	**18 (2)**	**15 (2)**	31 (4)
Vertical	13(2)	15 (2)	6 (3)	**0 (2)** ^{B}	2 (2)	**15 (2)**	**12 (2)**	28 (4)
Swipe Direction								
P-value	0.08	0.20	0.74	0.19	0.49	0.11	0.24	0.13
N-Medial	13(2)	14 (2)	6 (3)	4 (2)	1 (2)	17 (2)	16 (2)	31 (4)
R-Radial	12(2)	15 (2)	6 (3)	3 (2)	2 (2)	16 (2)	14 (2)	30 (4)

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet size (2 levels), Tablet Orientation (2 levels), Swipe Location (4 levels), Swipe Orientation (2 levels), Swipe Direction (2 levels) as fixed effect. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Table 4.3b: Thumb and wrist movement range (90^{th} %ile – 10^{th} %ile): Across participant marginal means and standard errors for ANOVA results

	Wrist		CMC			MCP		IP
	Extension(°)	Adduction(°)	Extension(°)	Abduction(°)	Pronation(°)	Flexion(°)	Abduction(°)	Flexion (°)
Tablet Size								
P-value	0.27	0.79	0.40	0.77	0.52	0.44	0.45	0.17
8”	10 (1) ^{B}	9 (1)	12 (1)	13 (2)	15 (2)	17 (2)	16 (2)	14 (2)
10”	10 (1)^{A}	10 (1)	12 (1)	14 (2)	14 (2)	17 (2)	15 (2)	15 (2)
Tablet Orientation								
P-value	0.51	0.83	0.27	0.58	0.39	0.18	0.58	0.74
Portrait	10(1)	10 (1)	12 (1)	12 (2)	14 (2)	18 (2)	15 (2)	15 (2)
Landscape	11(1)	10 (1)	13 (1)	14 (2)	14 (2)	17 (2)	14 (2)	15 (2)
Swipe Location								
P-value	**<0.0001**	0.05	0.08	**<0.022**	0.07	0.14	0.32	**<0.0001**
1 (Top left)	**13 (1)** ^{A}	12 (1) ^{A}	13 (1)	**15 (2)** ^{A}	16 (2)	18 (2)	17 (2)	**20 (2)**^{A}
2 (Top right)	**9 (1)** ^{B}	10 (1) ^{B}	12 (1)	**10 (2)** ^{C}	14 (2)	18 (2)	16 (2)	**13 (2)**^{B}
3 (Bot left)	**13 (1)** ^{A}	12 (1) ^{A}	13 (1)	**13 (2)**^{B}	15 (2)	19 (2)	17 (2)	**18 (2)**^{A}
4 (Bot right)	**8 (1)** ^{B}	9 (1) ^{B}	11 (1)	**10 (2)** ^{C}	14 (2)	20 (2)	15 (2)	**12 (2)**^{B}
Swipe Orientation								
P-value	0.12	0.28	0.11	**<0.0001**	0.22	**<0.0001**	**<0.0001**	**<0.0001**
Horizontal	10(1)	10 (1)	14 (1)	**15 (2)** ^{A}	16 (2)	**16 (2)**^{B}	**16 (2)**^{A}	**13 (2)** ^{B}
Vertical	11(1)	10 (1)	12 (1)	**10 (2)** ^{B}	15 (2)	**20 (2)**^{A}	**10 (2)**^{B}	**18 (2)**^{A}
Swipe Direction								
P-value	0.21	0.36	0.74	0.12	0.69	0.18	0.77	0.51
N-Medial	10(1)	10 (1)	12 (1)	14 (2)	15 (2)	18 (2)	16 (2)	14 (2)
R-Radial	10(1)	11 (1)	12 (1)	13 (2)	15 (2)	19 (2)	15 (2)	15 (2)

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet size (2 levels), Tablet Orientation (2 levels), Swipe Location (4 levels), Swipe Orientation (2 levels), Swipe Direction (2 levels) as fixed effect. Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Muscle activity

For median muscle activity, all measured forearm muscles except for flexor carpi radialis had significant differences across swipe locations. For all the measured muscles including extensor digitorum, extensor carpi radialis, extensor carpi ulnaris, extensor pollicis bravis, abductor pollicis longus, flexor digitorum superficialis and flexor carpi ulnaris, the top left swipe location had the greatest muscle activity while the bottom right swipe location had the smallest (Table 4.4a). Vertical swipe associated with smaller extensor digitorum and extensor pollicis brevis muscle activity. Interaction between swipe location and swipe orientation was significant for extensor carpi radialis, extensor pollicis bravis, flexor digitorum superficialis and flexor carpi ulnaris (Figure 4.2).

10” tablet associated with greater muscle activity compared to 8” tablet for all measured muscles except for extensor pollicis bravis. Portrait tablet orientation associated with greater extensor (extensor carpi radialis and extensor carpi ulnaris) but smaller flexor (flexor digitorum superficialis) muscle activity. Radial swipe action associated with greater forearm muscle activity for all measured muscles except for flexor carpi radialis, compared to medial swipe action (Table 4.4b). None of any other two-way or higher level interactions were significant.

Similar to the median, 90th percentile muscle activities differed significantly across almost all forearm muscles measured (Table 4.5a). For all but flexor carpi radialis, the top left swipe location had the greatest muscle activities while the bottom right location had the smallest. Horizontal swipe actions yielded greater muscle activities for all extensor muscles, but smaller muscle activities for flexor carpi radialis and flexor carpi ulnaris, compared to vertical swipe actions. Significant interactions were found between swipe location and swipe orientation for all muscles measured except for extensor digitorum and flexor carpi radialis.

10” tablet associated with greater 90th percentile muscle activity compared to 8” tablet for extensor carpi radialis, extensor carpi ulnaris, flexor carpi radialis and flexor carpi ulnaris (Table 4.5b). Tablet orientation yielded no difference across all measured muscles. Radial swipe action associated with greater forearm muscle activity for all measured muscles except for flexor carpi radialis, compared to medial swipe action (Table 4.5b). None of any other two-way or higher level interactions were significant.

For 10th percentile muscle activity, swipe location had little effect except for extensor digitorum and flexor carpi radialis (4.6a). Tablet size had the greatest impact with 10" tablet having greater muscle load across all measure muscles compared to the 8". Portrait orientation had greater 10th percentile muscle activities for extensor digitorum, extensor carpi radialis, extensor carpi ulnaris, abductor pollicis longus and flexor carpi ulnaris, compared to landscape orientation. Swipe orientation and swipe direction yielded no difference. None of the interaction terms were found significant for 10th percentile muscle activity data.

Task completion time

Completion time (1117ms for five repeated gestures) for gestures in the top left swipe location was significantly greater than those in the bottom right swipe location (862ms). Participants also completed faster when gestures were in the medial direction (918ms) compared to radial (1050ms) (Table 4.7).

User perception

Gestures done further from the hand associated with greater discomfort level (2.5) compared to closer to the hand (0.98). Actions in the horizontal direction also associated with greater discomfort level (2.0) compared to vertical direction (1.5) (Table 4.8).

Table 4.4a: Median Muscle Activity: Across participant marginal means and standard errors for RMANOVA Swipe Location, Swipe Orientation and Interaction

	Swipe Location					Swipe Orientation			Interaction
Median EMG activity (% MVC)	P-Value[1,2]	1	2	3	4	P-Value	Horizontal	Vertical	Zone x Direction
Extensor Digitorum	**<0.0001**	**6.4(1)[A]**	**3.9(1)[B]**	**4.3(1)[B]**	**2.9(1)[C]**	**0.0290**	**4.6(1)[A]**	**4.2 (1)[B]**	0.5500
Extensor Carpi Radialis	**<0.0001**	**6.0(1)[A]**	**5.0(1)[C]**	**5.5(1)[B]**	**4.5(1)[D]**	0.6200	7.0(1)	6.9(1)	**0.0054**
Extensor Carpi Ulnaris	**<0.0001**	**11(1)[A]**	**7.2(1)[B]**	**7.5(1)[B]**	**4.8(1)[C]**	0.1400	7.8(1)	7.4(1)	0.1131
Extensor Pollicis Brevis	**<0.0001**	**12(2)[A]**	**10(2)[B]**	**11(2)[B]**	**9(2)[C]**	**0.0190**	**11(2)[A]**	**10(2)[B]**	**0.0002**
Abductor Pollicis Longus	**<0.0001**	**8.6(1)[A]**	**6.2(1)[C]**	**7.0(1)[B]**	**5.3(1)[D]**	0.3700	6.9(1)	6.7(1)	0.2500
Flexor Digitorum Superficialis	**<0.0001**	**6.1(1) [A]**	**4.6(1)[C]**	**5.2(1)[B]**	**4.2(1)[C]**	0.3800	5.1(1)	5.0(1)	**<0.0001**
Flexor Carpi Radialis	0.4300	6.8(1)	7.0(1)	7.1(1)	7.0(1)	0.6200	7.0(1)	6.9(1)	0.1400
Flexor Carpi Ulnaris	**<0.0001**	**5.6(1) [A]**	**4.4(1)[C]**	**4.9(1)[B]**	**4.1(1)[C]**	0.6600	4.7(1)	4.8(1)	**0.0002**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Swipe Location (4 levels), Swipe Orientation (2 levels). Bold values indicate a significant effect (p<0.05).

[2]For significant main effects, Tukey's Post-Hoc groupings are ranked such that A>B>C>D. Values with the same superscript letters indicate no significant difference.

Table 4.4b: Median Muscle Activity: Across participant marginal means and standard errors for RMANOVA Size, Orientation, and Swipe Direction

	Tablet Size			Tablet Orientation			Swipe Direction		
Median EMG (% MVC)	P-Value[1,2]	10”	8”	P-Value	Landscape	Portrait	P-Value	Normal	Reverse
Extensor Digitorum	**0.0007**	**4.6 (1)^{A}**	**4.1 (1)^{B}**	0.6400	4.3 (1)	4.4 (1)	**<0.0001**	**3.8(1)^{B}**	**4.9 (1)^{A}**
Extensor Carpi Radialis	**<0.0001**	**5.8 (1)^{A}**	**4.8 (1)^{B}**	**0.0042**	**5.2 (1)^{B}**	**5.4 (1)^{A}**	**<0.0001**	**5.0(1)^{B}**	**5.5(1)^{A}**
Extensor Carpi Ulnaris	**<0.0001**	**8.2(1)^{A}**	**7.0(1)^{B}**	**<0.0001**	**7.0(1)^{B}**	**8.1(1)^{A}**	**<0.0001**	**6.7(1)^{B}**	**8.5(1)^{A}**
Extensor Pollicis Brevis	0.4800	11(2)	11(2)	0.0800	11(2)	10(2)	**<0.0001**	**10(2)^{B}**	**11(2)^{A}**
Abductor Pollicis Longus	**<0.0001**	**7.3(1)^{A}**	**6.3(1)^{B}**	0.3800	6.7(1)	6.9(1)	**<0.0001**	**6.3(1)^{B}**	**7.2(1)^{A}**
Flexor Digitorum Superficialis	**<0.0001**	**5.3(1)^{A}**	**4.7(1)^{B}**	**0.0380**	**5.1(1)^{A}**	**4.9(1)^{B}**	**<0.0001**	**4.5(1)^{B}**	**5.6(1)^{A}**
Flexor Carpi Radialis	**<0.0001**	**7.5(1)^{A}**	**6.4(1)^{B}**	0.9900	7.0(1)	7.0(1)	0.90	7.0(1)	6.9(1)
Flexor Carpi Ulnaris	**<0.0001**	**5.2(1)^{A}**	**4.4(1)^{B}**	0.5300	4.8(1)	4.7(1)	**<0.0001**	**4.4(1)^{B}**	**5.1(1)^{A}**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet Size (2 levels) and Tablet Orientation (2 levels) and Swipe Direction (2 levels). Bold values indicate a significant effect (p<0.05). Portrait vs landscape not significant. No two-way nor three-way interaction was detected

[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Table 4.5a: Ninetieth Percentile Muscle Activity: Across participant marginal means and standard errors for RMANOVA Swipe Location, Swipe Orientation and Interaction

	Swipe Location					Swipe Orientation			Interaction
90th %ile EMG (% MVC)	P-Value[1,2]	1	2	3	4	P-Value	Horizontal	Vertical	Zone x Direction
Extensor Digitorum	**<0.0001**	**19(2)^{A}**	**11(2)^{C}**	**14(2)^{B}**	**8 (2)^{D}**	**0.0002**	**14(2)^{A}**	**12 (2)^{B}**	0.06
Extensor Carpi Radialis	**<0.0001**	**11(1)^{A}**	**8.6(1)^{C}**	**9.9(1)^{B}**	**7.5(1)^{D}**	**0.0001**	**9.5(1)^{A}**	**8.8(1)^{B}**	**0.0044**
Extensor Carpi Ulnaris	**<0.0001**	**42(4)^{A}**	**28(4)^{C}**	**31(1)^{B}**	**19(1)^{D}**	**<0.0001**	**31(4)^{A}**	**28(4)^{B}**	**0.0007**
Extensor Pollicis Brevis	**<0.0001**	**27(3)^{A}**	**22(3)^{B}**	**22(3)^{B}**	**18(3)^{C}**	**<0.0001**	**24(3)^{A}**	**21(3)^{B}**	**0.0004**
Abductor Pollicis Longus	**<0.0001**	**21(3)^{A}**	**15(3)^{B}**	**17(3)^{B}**	**11(3)^{D}**	0.3700	17 (3)	15 (3)	**0.0289**
Flexor Digitorum Superficialis	**<0.0001**	**17(2)^{A}**	**12 (2)^{C}**	**15(2)^{B}**	**11 (2)^{C}**	0.0710	14 (2)	13(2)	**<0.0001**
Flexor Carpi Radialis	0.3400	10(1)	10(1)	10(1)	10(1)	**<0.0001**	**10(1)^{B}**	**11(1)^{A}**	0.08
Flexor Carpi Ulnaris	**<0.0001**	**13(1)^{A}**	**10(1)^{B}**	**11(1)^{B}**	**8(1)^{C}**	**0.0007**	**10(1)^{B}**	**11(1)^{A}**	**<0.0001**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Swipe Location (4 levels), Swipe Orientation (2 levels). Bold values indicate a significant effect (p<0.05).

[2]For significant main effects, Tukey's Post-Hoc groupings are ranked such that A>B>C>D. Values with the same superscript letters indicate no significant difference.

Table 4.5b: Ninetieth Percentile Muscle Activity: Across participant marginal means and standard errors of 10th Percentile for RMANOVA Size, Orientation, and Swipe Direction

	Tablet Size			Tablet Orientation			Swipe Direction		
90th %ile EMG (% MVC)	P-Value[1,2]	10”	8”	P-Value	Landscape	Portrait	P-Value	Normal	Reverse
Extensor Digitorum	0.9300	13 (2)	13 (2)	0.1000	14 (2)	13 (2)	**<0.0001**	**11(2)[B]**	**15 (2)[A]**
Extensor Carpi Radialis	**<0.0001**	**9.5 (1)[A]**	**8.8 (1)[B]**	0.0680	3.3 (1)	9.0 (1)	**<0.0001**	**8.5(1)[B]**	**9.8(1)[A]**
Extensor Carpi Ulnaris	**0.0006**	**29(4)[A]**	**31(4)[B]**	0.1400	30(4)	29(4)	**<0.0001**	**26 (4)[B]**	**34(4)[A]**
Extensor Pollicis Brevis	0.5600	22(3)	22(3)	0.0900	23(3)	22(3)	**<0.0001**	**19(3)[B]**	**25(3)[A]**
Abductor Pollicis Longus	0.3300	16 (3)	16 (3)	0.2600	16(3)	16(3)	**<0.0001**	**14(3)[B]**	**18(3)[A]**
Flexor Digitorum Superficialis	0.5100	14 (2)	13 (2)	0.2000	14 (2)	13 (2)	**<0.0001**	**12(1)[B]**	**15(1)[A]**
Flexor Carpi Radialis	**<0.0001**	**11(1)[A]**	**10(1)[B]**	0.6200	10(1)	10(1)	0.4700	10(1)	10(1)
Flexor Carpi Ulnaris	**<0.0001**	**11(1)[A]**	**10(1)[B]**	**0.0260**	**10(1)[B]**	**11(1)[A]**	**<0.0001**	**9(1)[B]**	**12(1)[A]**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet Size (2 levels) and Tablet Orientation (2 levels) and Swipe Direction (2 levels). Bold values indicate a significant effect (p<0.05). Portrait vs landscape not significant. No two-way nor three-way interaction was detected

[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Table 4.6a: Tenth Percentile Muscle Activity: Across participant marginal means and standard errors for RMANOVA Swipe Location, Swipe Orientation and Interaction

	Swipe Location					Swipe Orientation		
10th %ile EMG (% MVC)	P-Value[1,2]	1	2	3	4	P-Value	Horizontal	Vertical
Extensor Digitorum	**0.0360**	**1.6(0.2)^{A}**	**1.5(0.2)^{AB}**	**1.5(0.2)^{AB}**	**1.4(0.2)^{B}**	0.0790	1.6(0.2)	1.5 (0.2)
Extensor Carpi Radialis	0.2500	3.4(1)	3.5(1)	3.5(1)	3.3(1)	0.1400	3.5(1)	3.4(1)
Extensor Carpi Ulnaris	0.2000	2.2(0.3)	2.2(0.3)	2.2(0.3)	2.1(0.3)	0.5100	2.2(0.3)	2.2(0.3)
Extensor Pollicis Brevis	0.0590	5.9(1)	5.9(1)	6.1(1)	5.8(1)	0.9000	5.9(1)	5.9(1)
Abductor Pollicis Longus	0.1200	3.3(1)	3.2(1)	3.2(1)	3.1(1)	0.2800	3.3(1)	3.2(1)
Flexor Digitorum Superficialis	0.1700	2.3(0.4)	2.2(0.4)	2.3(0.4)	2.2(0.4)	0.8100	2.3 (0.4)	2.3(0.4)
Flexor Carpi Radialis	**0.0330**	**4.9(1)^{B}**	**5.3(1)^{A}**	**5.1(1)^{AB}**	**5.2(1)^{AB}**	0.2400	5.2(1)	5.1(1)
Flexor Carpi Ulnaris	0.4600	2.5(0.3)	2.4(0.3)	2.5(0.3)	2.4(0.3)	0.8300	2.5(0.3)	2.4(0.3)

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Swipe Location (4 levels), Swipe Orientation (2 levels). Bold values indicate a significant effect ($p<0.05$).

[2]For significant main effects, Tukey's Post-Hoc groupings are ranked such that A>B>C>D. Values with the same superscript letters indicate no significant difference.

Table 4.6b: Tenth Percentile Muscle Activity: Across participant marginal means and standard errors of 10^{th} Percentile for RMANOVA Size, Orientation, and Swipe Direction

	Tablet Size			Tablet Orientation			Swipe Direction		
10^{th} %ile EMG (% MVC)	P-Value[1,2]	10”	8”	P-Value	Landscape	Portrait	P-Value	Normal	Reverse
Extensor Digitorum	**<0.0001**	**1.6 (0.2)^A**	**1.4(0.2)^B**	**0.001**	**1.5 (0.2)^B**	**1.6 (0.2)^A**	0.1200	1.5(0.2)	1.6(0.2)
Extensor Carpi Radialis	**<0.0001**	**3.7 (1)^A**	**3.1 (1)^B**	**<0.0001**	**3.2 (1)^B**	**3.7 (1)^A**	0.7800	3.4(1)	3.4(1)
Extensor Carpi Ulnaris	**<0.0001**	**2.4(0.3)^A**	**2.0(0.3)^B**	**<0.0001**	**2.1(0.3)^B**	**2.3(0.3)^A**	0.5900	2.2(0.3)	2.2(0.3)
Extensor Pollicis Brevis	**<0.0420**	**6.0(1)^A**	**5.8(1)^B**	0.1500	6.0(1)	5.9(1)	0.1200	6.0(1)	5.9(1)
Abductor Pollicis Longus	**<0.0001**	**3.4(1)^A**	**3.0(1)^B**	**<0.0001**	**3.1(1)^B**	**3.4(1)^A**	0.6300	3.2(1)	3.2(1)
Flexor Digitorum Superficialis	**0.0001**	**2.3(0.4)^A**	**2.2(0.4)^B**	0.5200	2.2(0.4)	2.3(0.4)	0.3600	2.2(0.4)	2.3(0.4)
Flexor Carpi Radialis	**<0.0001**	**5.5(1)^A**	**4.8(1)^B**	0.1300	5.1(1)	5.2(1)	0.1100	5.0(1)	5.0(1)
Flexor Carpi Ulnaris	**<0.0001**	**2.8(0.3)^A**	**2.1(0.3)^B**	**<0.0001**	**2.3(0.3)^B**	**2.6(0.3)^A**	0.3800	2.4(0.3)	2.5(0.3)

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet Size (2 levels) and Tablet Orientation (2 levels) and Swipe Direction (2 levels). Bold values indicate a significant effect ($p<0.05$). Portrait vs landscape not significant. No two-way nor three-way interaction was detected

[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Table 4.7: Task completion time: Across participant marginal means and standard errors for ANOVA results

	Completion Time (millisecond)
Tablet Size	
P-value	0.35
8”	993 (50)
10”	974 (50)
Tablet Orientation	
P-value	0.10
Portrait	968 (53)
Landscape	1000 (53)
Swipe Location	
P-value	**<0.0001**
1 (Top left)	**1170 (55)^{A}**
2 (Top right)	**936 (55)^{C}**
3 (Bot left)	**968 (55)^{B}**
4 (Bot right)	**862 (55)^{D}**
Swipe Orientation	
P-value	0.06
Horizontal	963 (52)
Vertical	1005 (54)
Swipe Direction	
A P-value	**<0.0001**
Normal	**918 (53)^{B}**
Reverse	**1050 (53)^{A}**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet size (2 levels), Tablet Orientation (2 levels), Swipe Location (4 levels), Swipe Orientation (2 levels), Swipe Direction (2 levels) as fixed effect. Bold values indicate a significant effect ($p<0.05$).
[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B>C. Values with the same superscript letters indicate no significant difference.

Table 4.8 User perception of discomfort: Across participant marginal means and standard errors for ANOVA results

	Visual Analog Scale
	cm (out of 10cm)
Tablet Size	
P-value	0.33
8”	1.6 (0.2)
10”	1.7 (0.2)
Tablet Orientation	
P-value	0.65
Portrait	1.7 (0.3)
Landscape	1.7 (0.3)
Swipe Location	
P-value	**<0.0001**
Zone 1,3	**2.5 (0.3)^{A}**
Zone 2,4	**0.98 (0.3)^{B}**
Swipe Orientation	
P-value	**<0.0001**
Vertical	**1.5 (0.3)^{B}**
Horizontal	**2.0 (0.3)^{A}**

[1]Repeated Measures Multivariate ANOVA with participant as a random variable, Tablet size (2 levels), Tablet Orientation (2 levels), Swipe Location (2 levels), Swipe Orientation (2 levels) as fixed effect. Bold values indicate a significant effect (p<0.05).
[2]For significant main effects, Tukey’s Post-Hoc groupings are ranked such that A>B. Values with the same superscript letters indicate no significant difference.

Discussion

The aim of this study was to determine how tablet form factor and swiping gesture design affect thumb swiping performance, thumb posture, forearm muscle activity and self-reported discomfort for a two-handed tablet grip. Overall we saw effects of each of the independent variables, table form factor, tablet orientation, gesture location, gesture size, and gesture orientation on many of the thumb and wrist posture variables as well as the forearm muscles that articulate the joints of the wrist and thumb.

Consistent with our two hypotheses, the top left swipe location required significantly more extension and abduction across user's thumb joints, and it also required much greater forearm muscle activation, compared to the bottom right swipe location. In addition, the top left location resulted in the longest completion time for swipes, while the bottom right resulted in the shortest. User's wrist and thumb postures were closely related to the locations on the device. Swipe locations closer to the center of the tablet required users to exert greater wrist extension and adduction, greater thumb CMC and MCP abduction, and IP extension to reach the target with the thumb. The results corresponded with Trudeau et al.'s research when comparing a standard tablet soft keyboard versus a split soft keyboard during a two-handed tablet typing task (Trudeau, 2013). The authors found that a soft keyboard split to the side of the tablet effectively decreased thumb reaching compared to a regular one that requires hitting keys at the center of the tablet. Additionally, multiple studies reported that a southeast-northwest movement direction for thumb while using a mobile device to be the most difficult and requires the longest movement time (Karlson, 2006; Trudeau, 2012). With such an extreme thumb posture reaching to the tablet central area, the associated forearm muscle activation also elevated across all muscles except for flexor carpi radialis (Table 4.4a). In contrast, the bottom right swipe location, because of its proximity to the palm, allowed users to swipe with the smallest wrist joint angles and left the thumb MCP and IP joints more flexed (Trudeau, 2013), which in turn also resulted in the smallest muscle effort across the forearm muscles measured.

Compared to the 8” tablet, the 10” tablet required greater muscle load across all muscles measured to support the extra weight, but overall the tablet size had little impact on thumb posture or completion time. This was due to the fact that the target zone design was independent of the tablet size and therefore, the major difference between the two tablet sizes was the weight. The smaller muscle efforts associated with the smaller tablet were consistent with Pereira et al.’s research that found smaller muscle efforts of the tablet holding arm associated with smaller tablets (Pereira, 2013).

The tablet orientation had the greatest impact on the static muscle load (10^{th} percentile) with portrait orientation requiring greater muscle activation compared to landscape orientation. The current findings regarding greater muscle efforts associated with portrait orientation (Table 4b and 6b) are also consistent with what Trudeau et al. described in his study that users with a two-handed grip from the tablet bottom need to counter the increased moment arm with the hand supporting location being further away from the tablet center of mass(Trudeau, 2013). That moment arm is further increased when holding the tablet in the portrait orientation compared to the landscaped orientation.

The current study results imply that while manufacturers strive to improve tablet hardware form factors, software interface design can also significantly improve tablet user experience. By avoiding thumb reaching into the center area during a two-handed grip, users will be able to operate the tablet with a more neutral thumb and wrist posture, along with lower effort across forearm muscles.

In addition to showing how swipe location affects user biomechanics, the EMG interactions found between swipe location and swipe orientation were also informative. Both vertical and horizontal swipes showed similar trends across muscles where the top left swipe location required the greatest muscle effort and the bottom right swipe location required the least. Muscle efforts for the bottom left and top right swipe locations were somewhere between the top left and the bottom right swipe location. However, the increase in muscle effort from bottom right swipe location to the top left location was much more drastic for vertical swipes than horizontal swipes. From a software input design point of view, current study results serve as evidence that certain swipe orientation (vertical or horizontal) may be easier for users in certain locations of the tablet screen. Specifically, vertical thumb swipes in a two-handed grip can be utilized more when the target is closer to the palm, but should be avoided as the target get further away towards the geometric center of the tablet. Whereas, for horizontal swipe in some cases, the effect of swipe locations other than the top left location is not as significant.

The current study results need to be considered within the context of the study limitations. First, we only considered the two-handed grip support condition with only the thumb used for swipes. Hence, other support conditions such one-handed grip with index finger swiping or with the device supported on a desk, with or without a case, could potentially yield different results. Another limitation is that this was a laboratory study with a short duration of swiping tasks. The real life tablet swiping tasks could have different force requirement, duration, frequency and psychological stress level that could impact user's biomechanical loads. A next step following this study would be to compare the results from this study with different support conditions while interacting with other fingers. Longer tasks that better simulate real life office computer work with added psychological stress would also be appropriate. These data could potentially help tablet hardware and software manufacturers design tablet computer interface that allow improved performance and usability while inducing a more neutral hand and wrist posture with smaller muscle load demands.

The study found that the 10" tablet and the portrait orientation required greater muscle effort compared to 8" tablet and the landscape orientation, respectively. However, due to the tablet app design and time constraint, we chose a fixed dimension when defining swipe locations. Future study should consider varying the swipe location sizes based on different tablet size and orientation. Such information can provide insights regarding when swipe locations cease to matter with a specific tablet size and orientation.

Conclusion

The study results demonstrated that, for a two-handed grip on a tablet, thumb swiping time, thumb/wrist posture, forearm muscle activity, and self-reported discomfort vary across swipe locations.

Swipe location closest to the palm allows users to swipe with a more neutral thumb and wrist posture and requires less forearm muscle effort. As swipe location gets further either towards the upper edge or the center of the tablet, greater thumb extension and abduction along with greater wrist extension and adduction is require to reach the target. The forearm muscle activity would also increase significantly. Users had the shortest completion time when the swipe location was closest to their palm and they reported lower discomfort level when swipe location was closer to their palm.

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Discussion and Conclusion

Summary

The objectives of this dissertation were to determine the effects of specific workstation and device designs on users' posture, muscle activity and perceived-discomfort, especially those associated with upper extremities in order to identify opportunities to improve upper extremity biomechanics. Chapters 1 and 2 describe users' selected comfortable workstation set up affects the overall workstation design and device placement of sitting and standing computer workstations. The differences in workstation set up subsequently induced different user-adopted upper extremity posture and muscle activity, both in terms of magnitude and dynamic range. Chapter 3 describes how computer pointing devices of a seated computer workstation affect users' upper extremity biomechanics through their affordances, specifically in users' hand postures and forearm muscle activities. Chapter 4 describes tablet computer input interface's effects on users' forearm and hand posture and muscle loads, perceived-comfort level, and task completion time.

In Chapter 1, the standing posture identified that users preferred to have their workstations set up a bit lower, which in Chapter 2 was associated with improved shoulder posture affording lower shoulder muscle activity and load on the arms. We found that users selected different workstation set ups for sitting and standing computer workstations, based on their perceived-comfortable set up of an 8-hour work day. Chapter 2 built on these results by measuring the users' upper extremity posture and muscle activity while performing simulated office computer work. Through the two chapters, we found that while sitting, users placed the keyboard and mouse further with respect to their sternum, set the desk height slightly above their elbow height and the monitor slightly below their eye level, and adopted what resembled the OSHA-described "reclined sitting" posture. While standing, users placed the keyboard and mouse closer to their sternum, set the desk height slightly below their elbow height and the monitor further below their eye level, and adopted what resembled the OSHA-described "standing" posture. Comparing users' biomechanics between the two workstations, users while standing had a more relaxed and neutral shoulder posture, along with lower shoulder muscle activity of both sides, compared to sitting. Users while sitting had smaller wrist angles and lower wrist muscle activity.

In Chapter 3, we found that computer pointing device affordance significantly affect users' hand posture and forearm muscle activity. Specifically, the rollermouse device, which provided better forearm support and did not require users to hold the device, associated with the most neutral hand posture that left the fingers closer together and more flexed. It also associated with the smallest forearm muscle activities for the forearm muscles measured.

In Chapter 4, we found that tablet swipe location design when users held the device with two hands affected users' thumb posture, forearm muscle activity and swipe task completion time. The top left swipe location closer to the center of the tablet required significant greater thumb abduction and extension along with greater forearm muscle activities and longer task completion time, compared to the bottom right swipe location that was closer to the palm.

Contributions to Literature and Practice

These results provide an important contribution towards identifying ways to improve user's upper extremity biomechanics, from shoulder to hand, working with a wide variety of computer workstations. Chapters 1 and 2 signify one of the first biomechanics studies to utilize a psychophysical protocol to determine user's perceived comfortable computer workstation set up, specifically with regard to a standing workstation. The study also serves as important evidence in developing the standing computer workstation guideline that is currently lacking. Chapter 3 is the first study to evaluate four of the most popular computer pointing device designs currently on the market. The hand metric evaluation also was the first to quantify user's hand and finger posture to reflect the differences in forearm muscle efforts while using different devices. Finally, Chapter 4 is the first study to investigate how thumb swipe locations during a two-handed tablet grip can affect user's hand and thumb biomechanics, forearm muscle activity, and completion time.

In terms of practice, Chapters 1 and 2 demonstrated how a psychophysical protocol can be utilized in industry to inform user-perceived comfortable workstation set up. Chapter 3 showed why device-hand interaction needs to be understood for improvement of computer pointing device ergonomics. Chapter 4 showcased how touch-device software interface design can affect user's perceived comfort, biomechanical loads and performance. Using computer keyboard design as an example, future generations such as the portable keyboard for Microsoft Surface ® can utilize the hand metric developed in Chapter 3 to improve keyboard usability. Specifically, the ergonomics of the new keyboard can redesign keyboard curvature, key size, key spacing, and key pitch to induce a more neutral hand posture with smaller finger spread and extension. Additionally, future touch device interface and application development may utilize the methodologies showcased in Chapters 1, 2 and 4 to incorporate user's preference and perceived-comfort into design. By collecting direct feedback from users, touch device manufacturers can either redesign touch device software interface to maximize user's comfort, or simply provide more flexibility for users to design and/or arrange their input interface. Examples would include the ability to move the location of the virtual joystick during tablet computer gaming, and the freedom to arrange icon size and placement in the Android ® operating system (Google Inc.).

Limitations

The results presented in this dissertation need to be considered within the context of the study design. First, all data were collected in a laboratory setting with simulated tasks and a large amount of instrumentation attached to the test participants. Although we took steps to ensure that none of the attachments impeded any of user's range of motion, participants may have altered their behavior from how they would otherwise naturally interact with the devices. In addition, as we strove to mimic daily office computer work, real life work tasks may be different and have more psychological stress than what were included in our studies, and therefore may result in different measured outcomes. Nonetheless, the tasks chosen in the studies should be representative of what users may perform daily.

Since the relationship between MSD risks and the exposures to awkward posture and sustained muscle activity remains unknown, the muscle activity and postural differences across parameters found in our studies may have limited clinical relevance. Thus, a small percentage of MVC difference observed in our studies and its potential to cause elevated MSD risks remains unknown. However, it is generally believed that more awkward postures and higher muscle activity is associated with higher risk of MSD outcomes. There are also published reports that showed workplace interventions and alternative devices that do help induce better posture from users and also help people who have existing upper extremity pain to perform work tasks with less pain (Dardashti, 2003; Anderson et al., 2009; McLoone et al., 2009).

Future work

This dissertation provides valuable insights into how ergonomics of a computer workstation can be improved even as the technology within these workstations change, from the overall workstation set up to specific product design, to induce better user biomechanics and increase usability. However, much work remains to transfer the findings into practice. For example, ergonomic guidelines for standing computer workstation set up need to be developed to help users set up their workstation properly. Such guidelines can include data collected in Chapters 1 and 2 to incorporate user's direct feedback in order to maximize perceived-comfort. Similarly, future tablet research can incorporate the psychophysical concepts in Chapters 1 and 2 to investigate user's perceived comfortable interface and the resulting user biomechanical loads. Such information can help create better designs for tablet soft keyboards, tablet gaming interfaces and user-preferred app arrangement that may reduce risk of MSDs and boost work performance. Chapter 4 can also be expanded to investigate beyond the thumb interaction and different support conditions.

For hardware, future research can utilize the hand metric developed in Chapter 3 to improve alternative computer pointing devices like the trackball mouse. Various prototypes with different device shape, and different ball size and placement on the device can be evaluated help design new devices that can reduce finger spread and extension, and potentially provide better wrist and hand support to reduce forearm muscle loads. Future research in computer keyboards can also use similar metric developed in Chapter 3 to evaluate different designs such as comparing a "QWERTY" keyboard to a "DVORAK" keyboard, or comparing keyboards with different pitch and spacing. An example for such a study can utilize a repeated measure design and recruit participants to use both a “QWERTY” and a “DVORAK” keyboard to type up various articles presented at random. Hand and finger postures and forearm muscle loads will be the main quantitative measures to help investigate which design affords a more neutral hand posture and lower muscle loads. Users’ perception towards the comfort and difficulty levels should also be recorded. However, users’ familiarity with the “QWERTY” keyboard needs to be controlled and therefore a sufficient amount of training time needs to be granted for the “DVORAK” keyboard to ensure comparable typing performance.

Conclusion

This dissertation provides numerous original contributions to the fields of desktop and mobile computer ergonomics. The dissertation presents empirical results describing the complex interactions between users and their computer workstations, both as a whole and with specific components. The work in this dissertation contains the first study to utilize the psychophysical protocol to help develop guidelines for setting up a standing computer workstation. It also contains the first study to develop a quantitative measure showing how computer pointing devices interact with users’ hand and induce different levels of muscle load in the forearm. Lastly, it is the first study in the available literature to investigate how tablet swipe locations can affect users’ thumb, wrist and forearm biomechanics during a two-handed grip.

These new and practical contributions mark an important step toward developing new biomechanics based device designs and guidelines to help prevent MSDs of office computer users. They also demonstrate that ergonomics concepts can be used to design future generation technologies that fit users’ physical capabilities to reduce MSDs risk while promoting performance.

BIBLIOGRAPHY

Anderson, A.M., Mirka, G.A., Joines, M.B., Kaber, D.B. (2009). Analysis of alternative keyboards using learning curves. Human Factors: The Journal of the Human Factors and Ergonomics Society, 51 (1), 35-45.

ANSI/HFES 100 – 2007 Human Factors Engineering of Computer Workstations Published by the Human factors and Ergonomics Society, Santa Monica, CA,

Asundi, K., Odell, D., Luce, A. & Dennerlein, J. T. 2010. Notebook computer use on a desk, lap and lap support: effects on posture, performance and comfort. Ergonomics, 53, 74-82.

Asundi, K., Odell, D., Luce, A. & Dennerlein, J. T. 2012. Changes in posture through the use of simple inclines with notebook computers placed on a standard desk. Appl Ergon, 43, 400-7.

Brown, W. J., Miller, Y. D., & Miller, R. (2003). Sitting time and work patterns as indicators of overweight and obesity in Australian adults. International Journal Of Obesity And Related Metabolic Disorders: Journal Of The International Association For The Study Of Obesity, 27(11), 1340-1346.

Buckle, P. (2005). Ergonomics and musculoskeletal disorders: overview. Occupational Medicine, 55. doi:10.1093/occmed/kqi081

Burgess-Limerick, R., Mon-Williams, M., & Cappard, V. L. 2000. Visual display height. Human Factors, 42, 140–150.

Burgess-Limerick, R., Schemmell, J., Scadden, R., Plooy, A. 1999. Wrist posture during computer pointing device use. Clin. Biomech, 14**,** 280–286.

Camilleri M. and Rempel D., Self-Selected Display Configuration: Effect of Duration and Number-of-Displays. Proceedings of the Marconi Conference; 2011 January 28-30; Marshall, CA: Office Ergonomics Research Committe, Inc

Chau, J., Daley, M., Dunn, S., Srinivasan, A., Do, A., Bauman, A., and Ploeg, H. (2014). The effectiveness of sit-stand workstations for changing office workers' sitting time: Results from the Stand@Work randomized controlled trial pilot. International Journal of Behavioral Nutrition and Physical Activity, 11(1), 33-50.

Cho, C.-Y., Hwang, Y.-S., Cherng, R.-J. (2012). Musculoskeletal symptoms and associated risk factors among office workers with high workload computer use. Journal of Manipulative and Physiological Therapeutics, 35 (7), 534-540.

Colley, R. C., Garriguet, D., Janssen, I., Craig, C. L., & Clarke, J. 2011. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. Statistics Canada, Catalogue no. 82-003-XPE • Health Reports, Vol. 22, no. 1.

Cook, C., Burgess-Limerick, R., Chang, S. 2000. The prevalence of neck and upper extremity musculoskeletal symptoms in computer mouse users. Int. J. Ind. Ergon, 26, 347-356.

Dennerlein, J. T. & Johnson, P.W. 2006. Changes in upper extremity biomechanics across different mouse positions in a computer workstation. Ergonomics, 49**,** 1456-1469.

Gartner Research. 2014. Forecast: PCs, Ultramobiles, and Mobile Phones, Worldwide, 2011-2018, 2Q14 Update, Gartner, Inc. Stamford, Connecticut.

Gallagher, K.M., Campbell, T., Callaghan, J.P. (2014) The influence of a seated break on prolonged standing induced low back pain development. Ergonomics. DOI:10.1080/00140139.2014.893027

Gerr, F., Marcus, M., and Monteilh, C. 2004. Epidemiology of musculoskeletal disorders among computer users: lesson learned from the role of posture and keyboard use. Journal of Electromyography and Kinesiology, 14, 25-31.

Hagberg, M., Vilhemsson R., Wigaeus Tornqvist, E. & Toomingas, A. (2007). Incidence of self-reported reduced productivity owing to musculoskeletal symptoms: association with workplace and individual factors among computer users. Ergonomics, 50(11) 1820-34.

Hagberg, M., Wigaeus Tornqvist, E. & Toomingas, A. (2002). Self-reported reduced productivity due to musculoskeletal symptoms: associations with workplace and individual factors among white-collar computer users. Journal of Occupational Rehabilitation, 12(3) 151-162.

Harvey, R., Peper. E.,1997. Surface electromyography and mouse use position. Ergonomics, 40**,** 781-789.
Hermans, V., Hautekiet, M., Spaepen, A.J., 1998. Relation between posture and neck–shoulder muscular effort. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety, Vol. 202–205, IOS Press, pp. 202–205.
Houwink, A., Oudel Hengel, K.M., Odell, D., Dennerlein, J.T. (2009). Providing training enhances the biomechanical improvements of an alternative computer mouse design. Human Factors: The Journal of the Human Factors and Ergonomics Society, 51 (1), 46-55.
Huang, Y-d. Wang, S. Wang, T. He, L-h. 2012. Effects of backrest density on lumbar load and comfort during seated work. Chinese Medical Journal 125(19):3505-3508.
Ijmker, S., Huysmans, M.A., Blatter, B.M., Van Der Beek, A.J., Van Mechelen, W., Bongers 2007. Should office workers spend fewer hours at their computer? A systematic review of the literature. Occup. Environ. Med., 64**,** 211-222.
Jensen, C., Borg, V., Finsen, L., Hansen, K., Juul-Kristensen, B. 1998. Job demands, muscle activityand musculoskeletal symptoms in relation to work with the computer mouse. Scand. J. Work Environ. Health, 24**,** 418-424.
Karlqvist, L., Hagberg, M. and Selin, K. 1998. Computer mouse position as a determinant of posture, muscular load and perceived exertion. Scandinavian Journal of Work Environment & Health, 24**,** 62-73.
Kennedy C.A., Amick B.C., Dennerlein J.T., Brewer S., Catli S., Williams R., Serra C., Gerr F., Irvin E., Mahood Q., Franzblau A., Van Eerd D., Evanoff B., Rempel D.. Systematic review of the role of occupational health and safety interventions in the prevention of upper extremity musculoskeletal symptoms, signs, disorders, injuries, claims and lost time. Journal of Occupational Rehabilitation 2010; 20(2): 127-162.
Kingma, I. van Dieën, J. 2009. Sitting on an office chair versus sitting on an exercise ball. Appl. Ergon., 40 (2009), pp. 199–205
Kotani, K., Barrero, L.H., Lee, D.L., Dennerlein, J.T., 2007. Effect of horizontal position of the computer keyboard on upper extremity posture and muscular load during computer work. Ergonomics, 50, 1419-1432.
Kothiayal, K., Bjornerem, A.M. (2009). Effects of computer monitor setting on muscular activity, user comfort and aceeptability in office work. Work, 32 (2), 155-163.
Kuman, R., Kumar, S. 2008. A comparison of muscular activity involved in the use of two different types of computer mouse. Int J Occup Saf Ergon, 14, 305-311.
Lee, F. J., Mcloone H.E., Kotani K., Dennerlein J.T. 2007. Alternative computer mouse design and testing to reduce finger extensor muscle activity during mouse use. Human Factors, 49, 573-584.
Lee, T. 2005. Ergonomic comparison of operating a built-in touch-pad pointing device and a trackball mouse on posture and muscle activity. Percept Mot Skills, 101, 730-736.
Lee, Y., Su, M.C. 2008. Design and validation of a desk-free and posture-independent input device. Applied Ergonomics, 39, 399-406.
Lin, M., Liang, H., Lin, K., and Hwang, Y. 2004. Eletromyographical assessment on muscular fatigue – an elaboration upon repetitive typing activity. Journal of Electromyography and Kinesiology, 14, 661-669.
Lin M., Young J.G., Dennerlein J.T. 2015. Evaluating the effect of four different pointing device designs on upper extremity posture and muscle activity during mousing tasks. Applied Ergonomics. 47 259-264
Marcus, M., Gerr, F., Monteih, C. et al. 2002. A prospective study of computer users: II. Postural risk factors for musculoskeletal symptoms and disorders. American journal of industrial medicine. 41: 236-249.
Marshall, P.W.M., Patel H., Callaghan J.P. 2011. Gluteus medius strength, endurance, and coactivation in the development of low back pain during prolonged standing. Human Movement Science.30(1):63-73.

Matthews, C. E., Chen, K. Y., Freedson, P. S., Buchowski, M. S., Beech, B. M., Pate, R. R., & Troiano, R. P. 2008. Amount of time spent in sedentary behaviors in the United States, 2003- 2004. American Journal of Epidemiology, 167(7), 875-881.

McLoone, H.E., Jacobson, M., Clark, P., Opina, R., Hegg, C., Johnson, R. (2009). Design and evaluation of a curved computer keyboard. Ergonomics, 52 (12), 1529-1539.

Microsoft Corp. (2013). Reducing the incidence and cost of work-related musculoskeletal disorders with ergonomic input devices. Retrieved from http://www.microsoft.com/hardware/en-us/support/ergonomic-comfort

Musculoskeletal disorders. (2013). In Healthline. Retrieved from http://www.healthline.com/health/musculoskeletal-disorders#Definition1

Nelson-Wong, E., Callaghan, J.P. 2010. Is muscle co-activation a predisposing factor for low back pain development during standing? A multifactorial approach for early identification of at-risk individuals. J Electromyogr Kinesiol. 20(2):256-63.

Occupational Safety & Health Administration (n.d.). Computer workstations eTool. Retrieved from https://www.osha.gov/SLTC/etools/computerworkstations/components.html

Oude Hengel, K. M., Houwink, A., Odell, D., Van Dieen, J. H. & Dennerlein, J. T. 2008. Smaller external notebook mice have different effects on posture and muscle activity. Clin Biomech (Bristol, Avon), 23, 727-34.

Pain management: Musculoskeletal pain. (2015) In WebMD. Retrieved from http://www.webmd.com/pain-management/guide/musculoskeletal-pain

Pew Research 2013, Trend Data (Adults), Pew Internet & American Life Project, Washington, D.C.

Pereira, A., Miller, T., Huang, Y., Odell, D., Rempel, D. 2013. Holding a tablet computer with one hand: effect of tablet design features on biomechanics and subjective usability among users with small hands, Ergonomics 56(9) pp. 1363-75

Perotto, A., 1994. Anatomical Guide for the Electromyographer: The Limbs and Trunk. Charles C Thomas, Springfield, IL.

Pronk N.P., Katz A.S., Lowry M., Payfer J.R. Reducing Occupational Sitting Time and Improving Worker Health: The Take-a-Stand Project, 2011. Prev Chronic Dis 2012;9:110323.

Psihogios, J., Sommerich, C., Mirka, G., and Moon, S. 1998. The Effects of VDT Location on User Posture and Comfort: A Field Study. Human Factors and Ergonomics Society Annual Meeting, 871-875

Pynt, J. 2015. Rethinking design parameters in the search for optimal dynamic seating. Journal of Bodywork and Movement Therapies 19, 291-303.

Rempel, D., 2008. The split keyboard: An ergonomics success story. Hum Factors 50: 385-392.

Robertson, M., Ciriello, V., and Garabet, A. (2013). Officie ergonomics training and a sit-stand workstation: Effects on musculoskeletal and visual symptoms and performance of office workers. Applied Ergonomics, 44(1), 73-85

Robertson, M.M., O'Neill, M.J. (2003). Reducing musculoskeletal discomfort: effects of an office ergonomics workplace and training intervention. International Journal of Occupational Safety and Ergonomics, 9(4) 491-502.

Roelen, C. A. M., K. J. Schreuder, P. C. Koopmans, and J. W. Groothoff. 2008. "Perceived Job Demands Relate to Self-reported Health Complaints." Occupational Medicine 58 (1): 58–63.

Ryan, C. G., Grant, P. M., Dall, P. M., & Granat, M. H. (2011). Sitting patterns at work: objective measurement of adherence to current recommendations. Ergonomics, 54(6), 531‐538.

Sauter, S.L., Schleifer, L.M., & Knutson, S.J. (1991). Work posture, workstation design, and musculoskeletal discomfort in a VDT data entry task. Hum Factors, 33(2) 151-167.

Schüldt, K. Ekholm, J. Harms-Ringdahl, K. Németh, G. Arborelius, U.P. 1993. Effects of changes in sitting work posture on static neck and shoulder activity. Ergonomics Vol. 36 (7).

Shin, G., and Hegde, S. (2010). User-preferred display position: effects of display size. Human Factors 52(5):574-585.

Silfverberg, M., Mackenzie, I.S. & Korhonen, P. 2000, "Predicting Text Entry Speed on Mobile Phones", ACM, , April 1-6, 2000, pp. 9.

SJØGAARD, G., SØGAARD, K. 1998. Muscle injury in repetitive motion disorders. Clin. Orthop. Relat. Res., 351, 21-31.

Smith, M. J., Conway, F. T., & Karsh, B. T. (1999). Occupational stress in human computer interaction. Occupational stress in human computer interaction. Industrial Health, 37(2), 157 - 173. doi:10. 2486/indhealth.37.157

Snook, S.H., Vaillancourt, D.R., Ciriello ,V.M., Webster, B.S. (1995). Psychophysical studies of repetitive wrist flexion and extension. Ergonomics. 38(7):1488-1507. PMID: 7635136.

Sommerich, C. M., Heather S., Christy, A., Smith, C.S. 2002. Effects of notebook computer configuration and task on user biomechanics,productivity,and comfort. International Journal of Industrial Ergonomics, 30, 24.

Sommerich, C.M., Joines, S., Hermans, V., & Moon, S. 2000. Use of Surface Electromyography to Estimate Neck Muscle Activity. Eletromyography and Kinesiology, 10, 377-398.

Sommerich, C.M. (2002). A survey of desktop and notebook computer use by professionals. Proceedings of the Human Factors and Ergonomics Society, 46(13), 1124–1128. doi: 10.1177/154193120204601325

Srinivasan, D., Mathiassen, S.E. 2012. Motor variability in occupational health and performance. Clinical Biomechanics 27: 979–993.

Taillefer, F., Boucher, J.-P., Comtois, A. S., Zummo, M., & Savard, R. (2011). Réponses physiologiques et biomécaniques à divers types de bancs assis-debout chez les femmes avec et sans problèmes veineux. Le travail humain, Vol. 74(1), 31-58. doi:10.3917/th.741.0031

Thorp, A. A., Owen, N., Neuhaus, M., & Dunstan, D. W. (2011). Sedentary Behaviors and Subsequent Health Outcomes in Adults: A Systematic Review of Longitudinal Studies, 1996–2011. American Journal of Preventive Medicine, 41(2), 207-215. doi:10.1016/j.amepre.2011.05.004

Tissot, F., K. Messing, and S. Stock. 2009. “Studying the Relationship Between Low Back Pain and Working Postures Among Those Who Stand and Those Who Sit Most of the Working Day.”
Ergonomics 52 (11): 1402–1418.

Trudeau, M.B. (2013). Handheld device design affects thumb biomechanics (Unpublished doctoral dissertation). Harvard T.H. Chan School of Public Health, Boston, Massachusetts.

US Census Bureau. (2005). Computer and Internet Use in the United States: 2003. Retrieved from http://www.census.gov/prod/2005pubs/p23-208.pdf

Vink, P., Koningsveld, E.A.P., & Molenbroek, J.F. (2006). Positive outcomes of participatory

Warren, N.n.d.. University of Connecticut Health Center. Retrieved from http://www.oehc.uchc.edu/ergo_neutralposture.asp

Winter, D. 2005. Biomechanics and Motor Control of Human Movement-Third Edition.

Wobbrock, J.O., Myers, B.A. & Aung, H.H. 2008, "The performance of hand postures in front- and back-of-device interaction for mobile computing", International Journal of Human-Computer Studies, vol. 66, pp. 857-875.

World Health Organization. (2002). Physical inactivity a leading cause of disease and disability, warns WHO. Retrieved from http://www.who.int/mediacentre/news/releases/release23/en/

Young, J.G., Trudeau, M., Odell, D., Marinelli, K., and Dennerlein, J.T. (2012). Touch-Screen Tablet User Configurations and Case-Supported Tilt Affect Head and Neck Flexion Angles. Work: A Journal of Prevention, Assessment, and Rehabilitation, 41(1), pp. 81-91 DOI: 10.3233/WOR-2012-1337